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NATIONAL ENVIRONMENT COMMISSION
BHUTAN NATIONAL GREENHOUSE GAS PROJECT

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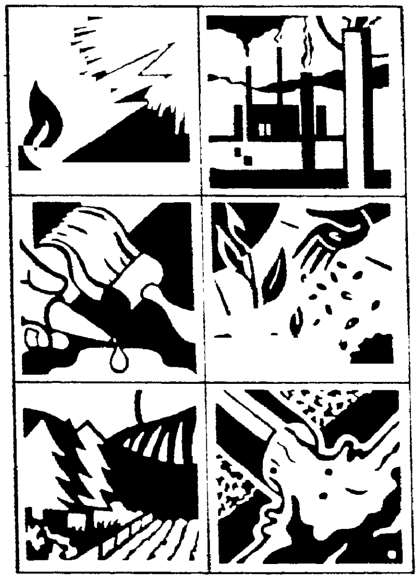
Greenhouse Gas Inventory Reference Manual



IPCC Guidelines for
National Greenhouse Gas Inventories

Volume 3

OECD
OCDE

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Whilst advice and information in these *Guidelines* is believed to be true and accurate at the date of going to press, neither the authors nor the publisher can accept any legal responsibility or liability for any errors or omissions that may be made.

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ACKNOWLEDGEMENTS

The present IPCC Guidelines for National Greenhouse Gas Inventories have been approved by the Scientific Assessment Working Group of the IPCC at Maastricht in September 1994 and subsequently adopted by the IPCC at its 10th session in Nairobi (10-12th November 1994). The Guidelines represent a first and substantial step towards the assembly and wide understanding of the methodologies needed for inventory construction. Their preparation has been a mammoth task involving many hundreds of experts and users and financial and other support from many countries and international organisations. I take this opportunity to acknowledge their financial and non-financial contributions and to thank all the donors sincerely. It would not be practical for me to name individually all those who have so willingly assisted this IPCC/OECD joint programme and helped to bring it to fruition. I would like, however, to identify the key groups and their leader, not only in their own rights but as the representatives of the many who have supported them

Financial support for the programme was provided by the United Nations Environment Programme/Global Environment Facility, the Environment Directorate of the Organisation for Economic Cooperation and Development, the International Energy Agency, the Commission of the European Communities, and the governments of Australia, Canada, France, Germany, Italy, Japan, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom and the United States of America. Significant non-financial contributions and resources in kind came from the European Environment Agency, IEA, OECD, UNEP, Japan, the Netherlands (in particular, the National Institute for Public Health and Environmental Protection or RIVM), the UK, and the USA.

The major, substantive content of the Guidelines was collected, assessed and assembled by groups of experts each covering the science of emissions within their specialist areas. The leaders of the groups are identified below and they wish to acknowledge, as I do, the crucial part played by the innumerable experts who enthusiastically helped in this undertaking.

The three volumes of the Guidelines were assembled and edited by the Technical Support Unit of Working Group I of the IPCC and the secretariats of the OECD and the IEA. I thank Paul Schwengels (Programme Manager), Jan Corfee-Morlot and Hans Sperling at the OECD and Tim Simmons and Karen Tréanton at the IEA for their leading roles. I, at the same time, recognise the unfailing support of their colleagues over the past three years.

Equally, I would like to express my gratitude to the IPCC/OECD Liaison Group (IOLG) responsible for steering the programme. The IOLG was chaired by Bruce Callander of the IPCC Working Group I Technical Support Unit and included the representatives of the OECD and IEA Secretariats and of donors. In particular, I thank Michael Short (UNEP), Jack Fitzgerald (US Country Studies Programme), Jan Feenstra (Netherlands Institute for Environmental Studies), Gordon McInnes (EEA) and Karl Jörss (German Federal Environment Agency).

These Guidelines form part of the IPCC Special Report to the first session (Berlin, 28 March to 7 April 1993) of the Conference of the parties to the UN Framework Convention on Climate Change. The other parts are:

- Report on Radiative Forcing of Climate Change 1994 with a Summary for Policymakers;
- An Evaluation of the IPCC 1992 Emission Scenarios also with a Summary for Policymakers;
- The IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.

The first two are published together and the last is a stand-alone volume. The Special Report was adopted by the IPCC at its tenth session (Nairobi, 10-12 November 1994).

Bert Bolin

Professor B Bolin
Chairman, IPCC

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Methane from Ruminant Animals and Waste
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Methane from Landfills and Wastewater Treatment
Co-chairs: Susan Thornloe and Elizabeth Aitchison

GHGs from Land Use Change, Forestry and Burning
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Methane from Industrial Sources
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Nitrous Oxide from Agricultural Soils
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Nitrous Oxide from Combustion and Industrial Processes
G De Soete and A McCulloch

PREFACE

Signature of the UN Framework Convention on Climate Change (UNFCCC) by around 150 countries in Rio de Janeiro in June 1992 indicated widespread recognition that climate change is potentially a major threat to the world's environment and economic development. Human activities have substantially increased atmospheric concentrations of greenhouse gases, thus perturbing the earth's radiative balance. According to projections from climate models, a global rise of temperature is a likely consequence. The potential impacts of climate change such as sea level rises and changes in local climate conditions including temperatures and precipitation patterns, could have important negative impacts on the socio-economic development of many countries.

The ultimate objective of the Convention is the stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system Such a level is to be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change The Convention also calls for all Parties to commit themselves to three objectives:

- To develop, update periodically, publish, and make available to the Conference of Parties their national inventories of anthropogenic emissions by sources and removals by sinks, of all greenhouse gases not controlled by the Montreal Protocol
- To use comparable methodologies for inventories of greenhouse gas emissions and removals, to be agreed upon by the Conference of Parties.
- To formulate, implement, publish and update regularly national programmes containing measures to mitigate climate change by addressing anthropogenic emissions.

The IPCC *Guidelines* are intended to assist the Parties directly in implementing the first two of these requirements. They have been under development for several years, in anticipation of this need.

By the time of the Second World Climate Conference in Geneva in October - November 1990, the need for a standard methodology for compiling national emission inventories was obvious. Under the auspices of the Organisation for Economic Co-operation and Development (OECD) and the International Energy Agency (IEA), with support from the USA, the UK and Norway, an initial compendium of methods was compiled. This document covered six direct and indirect greenhouse gases – carbon dioxide, methane, nitrous oxide, carbon monoxide, nitrogen oxide and non-methane volatile organic compounds. Chlorofluorocarbons (CFCs) and other substances already accounted for under the Montreal Protocol were intentionally excluded from the compendium. The document was discussed in detail by a meeting of experts (including many representatives of non-OECD countries) in Paris in February 1991. It was then adopted in a slightly modified form at the fifth session of the Intergovernmental Panel on Climate Change (IPCC) in March 1991 as the starting point for a set of IPCC *Guidelines* to be used by countries drawing up national inventories of greenhouse gas emissions and removals.

Development of the *Guidelines* has been undertaken by the Scientific Assessment Working Group (WGI) of the IPCC, working in close collaboration with the OECD and the IEA under the IPCC/OECD programme on emissions inventories. The objectives of the programme are:

- to develop and refine an internationally agreed methodology and software for calculation and reporting of national net emissions.
- to encourage widespread use of the methodology by countries participating in the IPCC and Parties to the UN Framework Convention on Climate Change.
- to establish procedures and a data management system for collection, review and reporting of national data.

The IPCC *Guidelines for National Greenhouse Gas Inventories* consist of three volumes: the *Greenhouse Gas Inventory Reporting Instructions*, the *Greenhouse Gas Inventory Workbook* and the *Greenhouse Gas Inventory Reference Manual*. The *Guidelines* include simple, default methods and assumptions covering the major sources and sinks of greenhouse gases, and also discuss more detailed methods. Countries have the option of using various methods and levels of detail depending on their own needs and capabilities. The *Guidelines* also provide a common reporting and documentation framework for all inventories. This is needed to allow for consistent comparison of national estimates even though they may have been prepared with varying methods.

It is essential that these *Guidelines* are approved internationally, and considerable effort has been expended to ensure this result. The methodology has been discussed, evaluated and refined through an international process which has included:

- wide dissemination of early drafts and collection of comments from national experts
- testing of methods through development of preliminary inventories
- country studies which ensure that methods are tested in a wide variety of national contexts
- technical workshops held in several locations including Western Europe, Africa, Latin America, Central Europe and Asia
- informal expert groups convened to recommend improvements on specific aspects of the methodology

The above activities all contributed to the development of the draft IPCC *Guidelines*. This draft was then circulated world-wide, in six UN languages for an extensive review by national and other technical experts. This review resulted in significant improvements to the *Guidelines*. The IPCC *Guidelines* were approved in November 1994 and then published. In March 1995, the Conference of the Parties of the Framework Convention on Climate Change will take a final decision about the use of the *Guidelines*, in connection with the UNFCCC.

The development of the IPCC *Guidelines* is an iterative process and Phase 1 of this process has now been completed. It is anticipated that the *Guidelines* will need to be updated periodically for several years as better data and scientific understanding support better estimation methods. Work is continuing on the development of improved methods that can be proposed, reviewed and approved by the IPCC in the future. From this point, the work of the IPCC/OECD programme will continue in several areas:

- some gases not covered in the current draft (e.g. hydrofluorocarbons - HFCs, tetrafluoromethane - CF_4, sulphur hexafluoride - SF_6, and hexafluoroethane - C_2F_6) will be added to the current methodology.
- some gases, e.g., nitrous oxide - N_2O will be given a more complete treatment in future supplements to the *Guidelines*.
- the current methodologies included in the *Guidelines* will be reviewed in the light of evolving scientific understanding and will be updated where appropriate.

Future work in the IPCC/OECD programme will continue to be supported by all of the mechanisms for international communication and consensus (e.g., expert groups, workshops, country studies) that have been used in the past The scope and timing of future updates to the IPCC *Guidelines* will be determined on the basis of guidance from the IPCC and in consultation with the INC/COP.

Contents of the IPCC Guidelines

All three volumes begin with the following sections:

Acknowledgements
Preface
Overview of the IPCC Guidelines

The contents of each volume are as follows:

Volume 1: Greenhouse Gas Inventory Reporting Instructions

Introduction to the Reporting Instructions
Chapter 1: Understanding the Common Reporting Framework
Chapter 2: Reporting the National Inventory
Tables: Standard Data Tables
  Summary Report Tables
  Overview Table
Annex 1: Managing Uncertainties
Annex 2. IPCC and CORINAIR Source Categories
Glossary

Volume 2: Greenhouse Gas Inventory Workbook

Introduction to the Workbook
Module 1 Energy
- Combustion-Related Emissions
- Fugitive Emissions

Module 2 Industrial Processes
- CO_2 from Cement Production

Module 3 Solvent and Other Product Use
Module 4 Agriculture
- Domestic Livestock
- Rice Cultivation
- Prescribed Burning of Savannas
- Field Burning of Agricultural Residues

Module 5: Land Use Change and Forestry
- Changes in Forest and Other Woody Biomass Stocks
- CO_2 Emissions from Forest and Grassland Conversion
- On-Site Burning of Forests: Emissions of Non-CO_2 Trace Gases
- Abandonment of Managed Lands

Module 6: Waste
- Land Disposal of Solid Waste
- Methane Emissions from Wastewater Treatment

Volume 3: Greenhouse Gas Inventory Reference Manual

Introduction to the Reference Manual
Chapter 1: Energy
Chapter 2: Industrial Processes
Chapter 3: Solvent and Other Product Use
Chapter 4: Agriculture
Chapter 5: Land Use Change & Forestry
Chapter 6: Waste

OVERVIEW OF THE IPCC GUIDELINES

This document is one volume of the *IPCC Guidelines for National Greenhouse Gas Inventories*.

The series consists of three books:

- THE GREENHOUSE GAS INVENTORY REPORTING INSTRUCTIONS
- THE GREENHOUSE GAS INVENTORY WORKBOOK
- THE GREENHOUSE GAS INVENTORY REFERENCE MANUAL

These books together provide the range of information needed to plan, carry out and report results of a national inventory using the IPCC system.

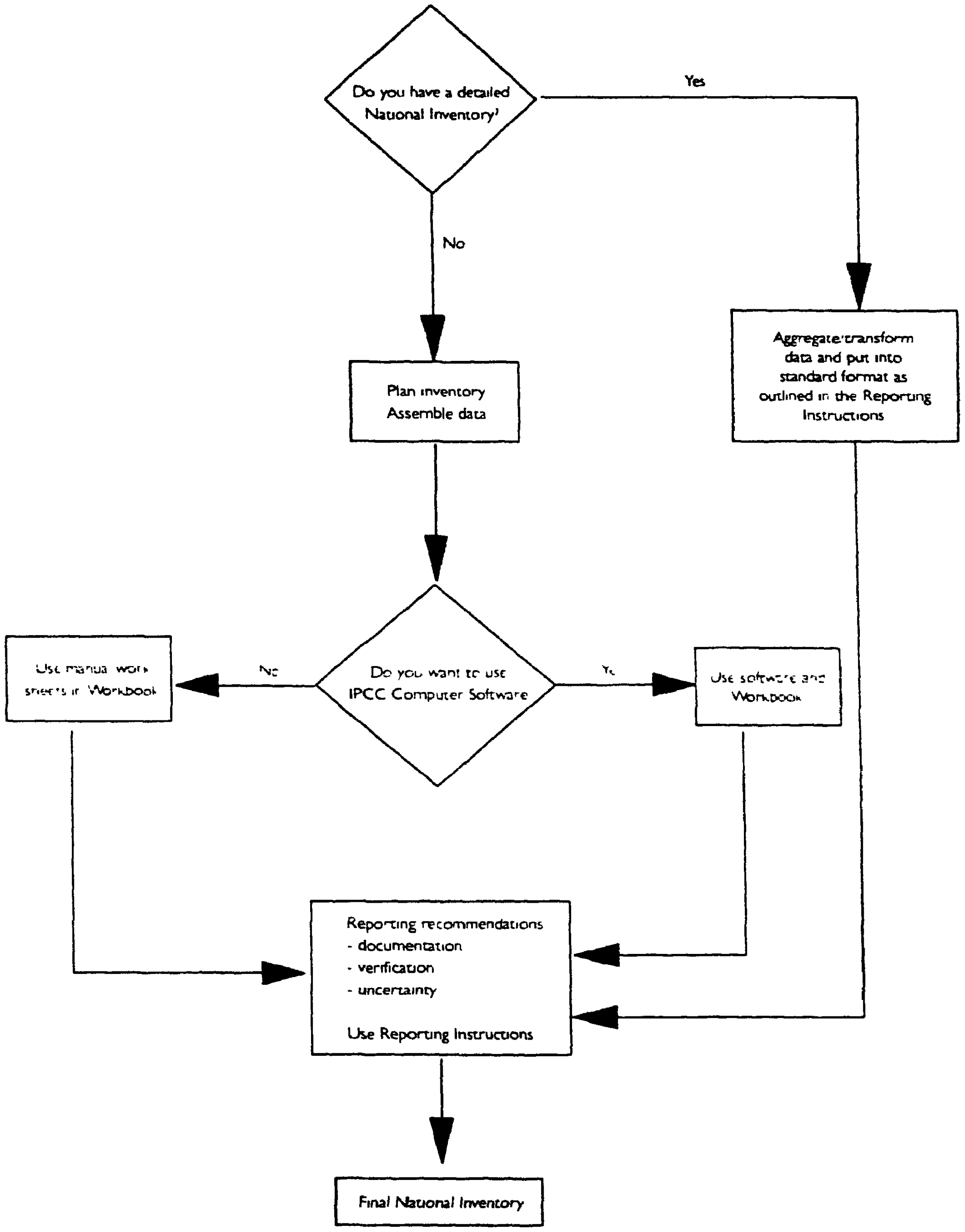
The *Reporting Instructions* (Volume 1) provides step-by-step directions for assembling, documenting and transmitting completed national inventory data consistently, regardless of the method used to produce the estimates. These instructions are intended for all users of the IPCC *Guidelines* and provide the primary means of ensuring that all reports are consistent and comparable.

The *Workbook* (Volume 2) contains suggestions about planning and getting started on a national inventory for participants who do not have a national inventory available already and are not experienced in producing such inventories. It also contains step-by-step instructions for calculating emissions of carbon dioxide (CO_2) and methane (CH_4), as well as some other trace gases, from six major emission source categories. It is intended to help experts in as many countries as possible to start developing inventories and become active participants in the IPCC/OECD programme.

The *Reference Manual* (Volume 3) provides a compendium of information on methods for estimation of emissions for a broader range of greenhouse gases and a complete list of source types for each. It summarises a range of possible methods for many source types. It also provides summaries of the scientific basis for the inventory methods recommended and gives extensive references to the technical literature. It is intended to help participants at all levels of experience to understand the processes which cause greenhouse gas emissions and removals to occur and the estimation methods used in compiling inventories.

Before you start...

This diagram explains the stages needed to make a national inventory which meets IPCC standards


Do you have a detailed National Inventory?
Yes
No
Aggregate/transform data and put into standard format as outlined in the Reporting Instructions
Plan inventory Assemble data
Do you want to use IPCC Computer Software
No
Yes
Use manual work sheets in Workbook
Use software and Workbook
Reporting recommendations
- documentation
- verification
- uncertainty
Use Reporting Instructions
Final National Inventory

The flow diagram above illustrates how the different types of users (working at different levels of inventory detail) can use the various volumes of the *Guidelines*. You should recognise that reality is more complex than this simple explanatory chart. Many countries may have some parts of the inventory complete at a high level of detail but may only be getting started on other parts. It is quite likely that some users will need to do several iterations of the thinking process reflected in the diagram with regard to different parts of their inventory.

The stages outlined in the flow diagram are:

Question 1
Do you have a detailed national inventory?

Answer: Yes

If your country already has a complete national inventory, you should transform the data it contains into a form suitable for use by IPCC. This means transforming it into a standard format. In order to do this, use Volume 1 of the *IPCC Guidelines, Reporting Instructions*. This gives details of the way in which data should be reported and documented.

Answer: No

You should start to plan your inventory and assemble the data you will need to complete the Worksheets in this book. Refer to the *Getting Started* section of the *Workbook*.

Question 2
Do you want to use the IPCC computer software?

Answer: Yes

If you want to use the IPCC software, you will still follow the instructions included in the *Workbook* to assemble the data you have collected into an inventory (see box). You will use the software instead of the printed worksheets to enter data.

Answer: No

If you do not use the IPCC software, use the *Workbook* and the Worksheets it contains to assemble the data you have collected into an inventory.

Finally...

Inventory data should be returned to IPCC in the form recommended in the *Reporting Instructions*. It is important that, where you have used a methodology other than the IPCC Default Methodology, it is properly documented. This will ensure that national inventories can be aggregated and compared in a systematic way in order to produce a coherent regional and global picture.

AVAILABILITY/USE OF COMPUTER SOFTWARE

IPCC computer software is available with the IPCC Guidelines. The software includes the same simple default methods as presented in the *Workbook* and the Standard Data Tables for reporting inventories, as presented in the *Reporting Instructions*. It is available in English only.

This version of the software should be run on a 386 based PC. The program requires a minimum of 570 kilobytes of free RAM and 2 Megabytes of EXTENDED RAM to run.

If you would like to receive a copy of the software, send a letter or fax to:

IPCC/OECD NATIONAL GHG INVENTORY PROGRAMME
Climate Change Division
OECD, Environment Directorate
2, rue André-Pascal
75775 PARIS CEDEX 16
FRANCE

FAX: (33-1) 45 24 78 76

General Notes on the Guidelines

Scope:

- The IPCC *Guidelines* are designed to estimate and report on national inventories of anthropogenic greenhouse gas emissions and removals. In general terms "anthropogenic" refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities. Users may include any human-induced emissions and removals in their inventory as long as they can be clearly documented and quantified.

- National inventories should include greenhouse gas emissions and removals taking place within national (including administered) territories and offshore areas over which the country has jurisdiction. There are, however, four qualifications of this principle in the *Guidelines*:

  (a) Emissions based upon fuel sold to ships or aircraft engaged in **international** transport should, as far as possible, not be included in national totals but reported separately.

  (b) Emissions from road vehicles should be attributed to the country where the fuel is loaded into the vehicle. The error in national emissions introduced in the case of road transport is expected to be small.

  (c) Emissions from the combustion or decay of wood and wood products are assumed to take place in the country in which the wood was harvested and within a year of harvesting. This is because it has been determined that the most workable approach to estimating CO_2 emissions and removals from forests is to account for changes in stocks of standing biomass in forests and other locations The simple assumption is that wood removed from stocks releases CO_2 emissions in the year and in the country where the wood was removed While the IPCC method allows for accounting of exports and carbon stored in products, it does not yet provide a methodology, which is a priority for future work

  (d) In line with the principle of national emissions, the IPCC methodology accounts for the bulk of greenhouse gas emissions related to fuel combustion in the country in which those emissions are released. The IPCC methodology for carbon stored in non-fuel products manufactured from fuels as raw materials takes into account emissions released from those products during their use or destruction. Emissions are attributed to the country where the conversion to non-energy products takes place, even when the products are traded internationally. This is believed to be a relatively small net error, but it is also a priority for future work.

Data Quality and Time Frame:

- The data available to estimate anthropogenic greenhouse gas emissions resulting from fuel combustion are generally of a better quality than the data available to estimate greenhouse gas emissions and removals in the areas of agriculture and land use change/forestry. Accordingly, while the IPCC *Guidelines* request an emission figure for a single year in most source/sink sectors, three-year averages (with the base year in the middle) are preferred in the areas of agriculture and land use change/forestry. In addition, the IPCC *Guidelines* recognise that greenhouse gas emissions and removals in the area of land use change/forestry can occur over an extended period of time once the activity has been completed. For example, when estimating emissions from the abandonment of forests and grasslands, users are requested to estimate emissions related to two time periods of previous activity: (a) 0 - 20 years ago, and (b) 20 - 100 years ago.

Default Method:

- The IPCC *Guidelines* contain "default" methodologies for the estimation of greenhouse gas emissions and removals. Users are encouraged to go beyond these minimum default methods where possible, and report the results.

  The IPCC *Guidelines* also include a number of "default" assumptions and data for use in the estimation of greenhouse gas emissions and removals. This default information is included primarily to provide users with a starting point from which they can develop their own national assumptions and data. Indeed, national assumptions and data are always preferred because the default assumptions and data may not always be appropriate for specific national contexts.

  In general, therefore, default assumptions and data should be used only when national assumptions and data are not available. Section 2 of the Introduction to the IPCC Greenhouse Gas Inventory *Workbook* provides information on the quality of the default data available in different greenhouse gas source/sink categories. When it is indicated that the data available are of low quality, users should recognise that the default data do not provide a basis for the development of a definitive inventory of that source/sink category.

- Many of the categories of greenhouse gas emissions and removals can be estimated only with large ranges of uncertainty. Quite naturally, some national experts have developed methods which are designed to produce ranges of estimates rather than point estimates for highly uncertain categories. The IPCC *Guidelines*, however, require that users provide a single point estimate for each gas and emissions/removal category. This is simply to make the task of compilation, comparison and evaluation of national reports manageable. Users are encouraged to provide uncertainty ranges or other statements of confidence or quality along with the point estimates. The procedures for reporting uncertainty information are discussed in the *Greenhouse Gas Inventory Reporting Instructions*.

Double Counting of Emissions:

The methods proposed for the estimation of emissions sometimes simplify the inventory construction in order to use data which are more readily available than those needed for a detailed and more precise approach. In certain cases this may cause or increase the risk of double counting emissions. There are two areas where this may occur in the *Guidelines*.

1) All countries preparing CO_2 inventories using the IPCC *Guidelines* are asked to estimate the emissions from fuel combustion using the IPCC Reference Approach either as the primary means of preparing the inventory or as a verification stage following the preparation of an inventory using national methods. The Reference Approach is a simple procedure which demands relatively little data and lends itself to wide-spread application as a "common denominator".

The Reference Approach provides an upper bound to CO_2 emissions inferred from the country's supply of fossil fuels by identifying the carbon content, subtracting from it the carbon stored in non-energy products and products made from fuels used as raw material, adjusting for carbon which remains unburnt and multiplying by 44/12. It is an upper bound[1] because some of the carbon will be emitted in forms other than CO_2, in part because fuel combustion is not always complete but also because fuels may leak or evaporate. Consequently the CO_2 emissions figure obtained from the Reference Approach will include carbon emitted as CH_4, CO or NMVOC. At the same time the *Guidelines* encourage countries to estimate separate inventories for these gases and when this is done these gases are reported twice, in their emitted form and as CO_2. It is in this sense that they are "double counted".

---

[1] In practice, because of inaccuracies in the supply statistics and/or emission factors, CO_2 estimates from the Reference Approach may be less than those obtained by summing all CO_2 emissions from the combustion of fuel.

Use of the Reference Approach carries with it two consequences which should be carefully noted.

Because the Reference Approach uses fossil fuel supply statistics as a basis for determining the carbon supply

- Not all carbon based emissions from fossil fuel are reported twice. The Reference Approach CO_2 estimate will not include emissions from combustion or release of fossil fuels for which the corresponding quantities (activity data) are not included in national production or import figures. Notable examples of activities which lead to emissions not included are the venting of natural gases from coal mining and handling and oil and gas production. Emissions from the flaring of natural gases are also excluded. As a result, when emissions from these activities are included in the relevant inventories using the fugitive emissions methodologies recommended in the *Guidelines* no "double counting" occurs.
- CO_2 emissions from biomass used as fuels are excluded from the total CO_2 emissions figure. The restriction of the Reference Approach to fossil fuels results from the sustainable nature of biofuels The CO_2 emissions are, however, reported for information purposes. Note that non-CO_2 emissions from biofuels are included in their respective inventories.

2) Double counting may also occur when *calculated* emissions from the manufacture of products from fuels used as raw materials or from the use of fuels for their physical properties (e.g. lubricants) include emissions produced from the later destruction of these products. The double count will be with any separate reporting within the Waste module of the *Guidelines* of emissions from destruction.

INTRODUCTION TO THE REFERENCE MANUAL

This *Reference Manual* is one of three volumes of the *IPCC Guidelines for National GHG Inventories*. It provides a compendium of information on the various human activities which cause greenhouse gas emissions or removals to occur. It builds on work carried out in preparation of the OECD Report: *Estimation of Greenhouse Gas Emissions and Sinks, Final Report From the OECD Experts Meeting, 18-21 February 1991*, (OECD, 1991). In August 1991, the IPCC/OECD joint programme distributed this document as a starting point for development of guidelines for national inventories of greenhouse gases. In some sections for which no recent methodologies are available, it incorporates text with very little change from that document. In some areas, detail presented in the earlier report is summarised here. The OECD (1991) document remains a valuable reference document for national experts and others interested in the development of the IPCC National GHG Inventory Methods. In particular, detailed discussions of the reasoning behind some of the technical decisions made early in the IPCC/OECD programme can be found there

Another major published resource document heavily used in the preparation of this *Manual* is the *Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide, Amersfoort, NL, 3-5 February 1993* (van Amstel, 1993) To provide technical information for improvement of the early methods known to be weak, the IPCC/OECD programme established informal expert groups to work toward reaching international agreement on proposed revisions to the guidelines. A major landmark in this effort was the Amersfoort workshop sponsored by the Dutch government and hosted by the Netherlands National Institute of Public Health and Environmental Protection (RIVM) National experts presented their findings at the workshop and then discussions were held in working group sessions. Their conclusions and recommendations have been drawn upon in the preparation of the *Guidelines*.

In preparing this document, the IPCC/OECD has also received valuable technical input from a number of other international workshops. The overall purpose of these workshops was to provide a forum for experts to discuss ways to improve the methodologies and reporting procedures and to ensure widespread participation in the development process. Many of the recommendations received have been incorporated into this revised *Reference Manual*.

In general, the basic approach to estimating national emissions is similar across the various gases and human activities which are sources or sinks. Fundamentally, emissions are a product of activity data and emission factors.

In reality, these calculations are often more complicated than this would indicate, with several steps being involved in the calculation of each of the general terms - activity data and emission factors. But it is useful to keep this general structure in mind as it provides an organising framework for all of the calculations and a means of evaluation and comparison.

The *Reference Manual* frequently provides a number of different possible methodologies or variations for calculating a given emission. In most cases these represent calculations of the same form but the differences are in the level of detail at which the original calculations are carried out. Wherever possible the methodology provides a "tiered" structure of calculations which describes and connects the various levels of detail at which national experts can work depending on the importance of the source category, availability of data, and other capabilities. All national experts are encouraged to work at the most detailed level which is possible and appropriate for their situation. The tiered structure ensures that estimates calculated at a very detailed level can be aggregated up to a common minimum level of detail for comparison with all other reporting countries.

The methodologies for the estimation of the emissions and removals of GHGs, which are presented and discussed in the *Guidelines*, are grouped by the main activity sectors, (chapters of this volume) namely, *Energy, Industrial Processes, Solvent and Other Product Use, Agriculture, Land Use Change and Forestry, and Waste*. In general, the source/sink activities are unique to their sector but there are cases, e.g., biomass burning, which occur in several sectors and are described in the chapters on *Land Use Change and Forestry, Energy* and *Agriculture*.

In summary, this *Guidelines* document draws on the input of expert groups and national experts from around the world. The methodologies presented offer a recommended process for estimating and tracking national emissions inventories. Along with offering the best current methodologies for developing consistent national inventories, these *Guidelines* discuss weaknesses in the existing methodologies and identify technical areas where additional work is needed to develop better methods in the future.

The chapters are divided by subject areas and correspond to the same subject chapters in the *Workbook*. This document should be used by national experts as a reference tool to accompany the *Workbook* and the *Reporting Instructions* when constructing and reporting national inventories of GHG emissions and removals.

References

OECD (1991), *Estimation of Greenhouse Gas Emissions and Sinks, Final Report from the OECD Experts Meeting, 18-21 February 1991*. The Organisation for Economic Co-operation and Development, Paris, France, revised August 1991.

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CHAPTER 1 ENERGY

1.1 Overview

This chapter discusses inventory methods for emissions of greenhouse gases from energy sources, including CO_2, CH_4, N_2O, NO_x, NMVOC and CO. Energy systems are extremely complex and pervasive components of national economies. The full range of greenhouse gases are emitted from energy production, transformation, handling and consumption activities. The various emissions from energy systems are organised in two main categories - 1) emissions from fuel combustion, and 2) non-combustion, or "fugitive" emissions.

In dealing with fuel combustion emissions, CO_2 is discussed in a separate section because it can be calculated accurately at a highly aggregated level, unlike other gases. CO_2 emissions are primarily dependent on the carbon content of the fuel The IPCC reference method for CO_2 emissions from fuel combustion is a simple, accurate and internationally transparent approach which takes advantage of this fact. Non-CO_2 greenhouse gases are more related to technology and combustion conditions, and hence, must be estimated from activity data which relate to those conditions.

CO_2 from energy activities can be estimated from energy supply data, with a few adjustments such as for carbon non-oxidised. Supply data for all commercial fuels are widely available from internationally-validated data bases for individual countries of the world. These data provide an accurate starting point for the estimation of CO_2 inventories However, since fuel qualities vary by region, so will their carbon content (emission factor). For global or regional estimations of CO_2, these variations will not significantly affect inventories. However, variations among the types of fuels consumed within the primary fuel categories from one nation to another will affect the accuracy of each national inventory. For example, certain countries may depend on lignite, whereas others will use only bituminous coals. As discussed later, the variation in emission factors within fuel categories can be as high as 10 per cent. As a result, national energy data and appropriate emission factors should reflect the actual mix of fuel types within each country.

Unlike CO_2, national inventories of CH_4, N_2O, NO_x, CO and NMVOCs require more detailed information. This is due to their dependence on several interrelated factors, including combustion conditions, technology, and emission control policies, as well as fuel characteristics. These gases cannot be estimated in the same manner as CO_2, as the use of a single emission factor for a particular fuel will not be sufficient to capture the dependence of the emissions on the conditions under which the fuel is used. On the other hand, CO_2 emissions can also be calculated at the more detailed level required for other gases. When national experts calculate other GHG emissions from fuel combustion at a detailed level, they should estimate CO_2 at the same time. Comparison and reconciliation of the aggregate and detailed CO_2 emissions calculations can serve as a valuable verification process. Procedures for estimating CO_2 at both levels of detail are discussed in this chapter. For all emissions estimates, the range of uncertainty should be stated to the extent feasible. *Volume 1: Reporting Instructions* discusses approaches for estimating and expressing uncertainty.

The non-CO_2 gases from fuel combustion are discussed according to two major combustion source categories: stationary sources and mobile sources. The use of these two main categories is the most common method for the initial disaggregation of fuel combustion activities. These two categories best represent differences in the types of service and capture technology differences.

A special section on traditional biomass fuels is included because they need to be treated differently from other stationary combustion sources. Considerable quantities of biomass fuels do not enter commercial markets and so their incidence, use and characteristics are poorly known.

In addition to the emission of greenhouse gases from fuel combustion GHGs may also be released into the atmosphere in an unplanned or a deliberate manner. These are fugitive emissions. Fugitive emissions are intentional or unintentional releases of gases from anthropogenic activities. In particular, they may arise from the production, processing, transmission, storage and use of fuels, and include emissions from combustion only where it does not support a productive activity (e.g., flaring of natural gases at oil and gas production facilities). The most significant greenhouse gas emissions in this category are methane emissions from coal mining and from oil and gas systems. There are also emissions of other gases, such as CO_2 and NMVOCs as fugitive or by-product emissions from energy systems.

1.1.1 Organisation of the Chapter

In addition to this introduction, this chapter is organised into six separate energy sections:

- **CO_2 emissions from energy**: CO_2 emissions from all combustion sources are estimated using an aggregate carbon balance approach to account for all carbon across all energy categories.
- **Greenhouse gas emissions from stationary sources**: Separated by common type of service sector, and further by technology, estimation of emissions from stationary source activities focuses on large facilities for NO_x and on the commercial and residential sectors for CO, CH_4 and NMVOC.
- **Greenhouse gas emissions from mobile sources**: Mobile source activities are divided by transport mode, vehicle type and size to characterise a diverse range of engine types and their respective emission characteristics.
- **Greenhouse gas emissions from burning traditional biomass fuels**: A simplified approach is provided because data are often inadequate for estimating emissions from this category based on technology-specific emission factors. This approach is designed to be used with data obtainable in developing countries where traditional fuels make up a large fraction of total energy use.
- **Fugitive emissions from coal mining and handling activities**: Emissions are generated as a result of the mining and handling of coal, primarily methane emissions from coal mining. Other emissions of GHG from coal mine and waste fires are briefly discussed.
- **Fugitive emissions from oil and natural gas activities**: Methane emissions from natural gas flaring and venting, and from natural gas production, transmission and distribution are the most important for this category. CO_2 emissions from venting and flaring are included as are NMVOC emissions from production, processing and distribution of oil and oil products.

1.2 Emission Factor Data

Emissions of GHGs from fuel combustion and fuel supply activities are calculated by multiplying levels of activity by emission factors. The most commonly used activity measure for energy-related emissions is the amount of fuel combustion or, where fugitive emissions are concerned, the amount of fuel produced or distributed. In some cases other measures of activity are used, most notably in calculating emissions from the transport sector. Emission factors are usually presented in the form of mass of pollutant per unit of activity (e.g., kg N_2O/TJ).

For CO_2 emission factors are a proxy for the amount of carbon in the fuel, but for all other gases emission factors are very dependent on other factors (e.g., combustion technology, combustion conditions, control technology). A number of international and national sources of energy activity data and industry emission factors exist largely as a result of international and national analyses of alternative control policies for SO_x, NO_x and NMVOC. A few sources have also recently emerged on various other GHGs. The more detailed factors (for gases other than CO_2) do not relate directly to national energy activity data described below, but require some additional information. The sources of emission factor data, and procedures for making these linkages are discussed in the context of specific gases and source types, in the relevant sections which follow.

1.3 Energy Activity Data

Subject to the requirements outlined below and intended to ensure the comparability of country inventories, the IPCC approach to the calculation of emission inventories encourages the use of fuel statistics collected by an officially recognised, national body as this is usually the most appropriate and accessible activity data In some countries, however, those charged with the task of compiling inventory information may not have ready access to the entire range of data available within their country and may wish to use data specially provided by their country to the international organisations whose policy functions require knowledge of energy supply and use in the world

There are, currently, two main sources of international energy statistics the International Energy Agency of the Organisation for Economic Co-operation and Development (OECD/IEA), and the United Nations (UN). The primary energy data sources cited in this report include:

- From the OECD/IEA· Energy Statistics and Balances for Non-OECD Countries (OECD/IEA, 1993*a*); Energy Balances of OECD Countries (OECD/IEA, 1993*b*); and Energy Statistics of OECD Countries (OECD/IEA, 1993c).
- From the United Nations: Energy Statistics Yearbook (UN, 1993).

Both international organisations collect energy data from the national administrations of their member countries through systems of questionnaires. The data gathered are therefore "official" data. To avoid duplication of reporting, where countries are members of both organisations, the UN receives copies of the IEA questionnaires for the OECD member countries rather than requiring these countries to complete the UN questionnaires. When compiling its statistics of non-OECD member countries the IEA, for certain countries, uses UN data to which it may add additional information obtained from the national administration, consultants or energy companies operating within the countries. Statistics for other countries are obtained directly from national sources. The number of countries covered by the IEA publications is fewer than that of the UN. [1]

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[1] Approximately 120 countries (of about 170 UN Member countries) are included in the IEA data, but the countries it includes account for about 98 per cent of worldwide energy consumption and nearly all energy production.

1.3.1 Comparability of Reporting

In order to meet the objectives of the IPCC/OECD programme, inventories must be readily comparable. This requires a large measure of commonality of definitions of activities (source/sink categories) and fuel product groups and the use of a reporting discipline which makes evident the construction of the inventory from the activity data. Specific guidelines for reporting have been prepared. In order to reduce the uncertainty created by possibly different definitions, the IPCC *Reporting Instructions* have largely adopted definitions utilised by the IEA for the regular collection of energy data from OECD member countries. The active co-operation between the UN Statistical Division (New York), the UNECE (Geneva), Eurostat and the IEA has ensured that there are now very few differences between the definitions employed by these organisations for the collection of their energy data. The IEA definitions may be found in the Glossary at the end of the *Reporting Instructions* (Volume 1).

Although common standards for the collection of data by international organisations exist the presentation of the data collected can be differently presented. At least five aspects of energy data presentations need to be checked prior to using data for greenhouse gas inventories:

- Are the energy data expressed in terms of net calorific values (NCV) or gross calorific values (GCV)?[2] Since most of the world uses net calorific values, the IPCC *Guidelines* uses net calorific values.
- Are vegetal waste or waste-derived fuels included if combusted for energy production? These fuels should be accounted for in the IPCC methodology, but are included with biomass fuels.
- Is non-energy fuel usage (if non-oxidised) accounted for?[3]
- How are international bunker fuels for air and ship transport treated?[4]
- Are non-commercial fuels, including wood and other biomass fuels, included?[5]

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[2] The IEA generally reports data in net calorific values. The difference between the net and the gross calorific value of a fuel is the heat of condensation of moisture in the fuel during combustion. The net calorific value excludes this. The IEA assumes that net calorific values are 5 per cent lower than gross calorific values for oil and coal, and 10 per cent lower for natural gas.

[3] This is normally reported in primary energy requirements but is not combusted and therefore does not contribute directly to greenhouse gas emissions.

[4] International bunker fuels are combusted in ships at sea and by airplanes (both undertaking international movements) and therefore should be included in global greenhouse gas estimations. The question is how to allocate emissions among nations or regions. Following guidance from the INC, the IPCC recommends that every country estimate emissions from international bunker fuels sold within national boundaries, but that these emissions would be reported separately and, as far as possible, excluded from national totals.

[5] While some of these fuels (such as wood) may be included in national or international data sets, it is likely that they are underestimated due to poor record-keeping and lack of statistical information for non-commercial fuels.

Given responses to these questions, several adjustments may need to be made to the energy data being used in order to formulate a complete inventory of greenhouse gases. If published IEA data are being used the following corrections must be made:

1 Consumption of vegetal fuels in non-OECD countries should be added to commercial fuel consumption. Estimates of the former are available in the IEA publication cited. Consumption of vegetal fuels, as declared by OECD countries in their reports to the IEA, are included as "Other Solid Fuels" in the IEA statistics for these countries.

2 Care is required when estimating the amount of fuel used without oxidation in the manufacture of non-energy products. IEA data generally cover only deliveries to the industry sector manufacturing such products. Some of the quantities delivered will be oxidised by the user.

3 IEA data do not include deliveries of oil for international air transport as part of the International Bunkers data. Separate estimates of these quantities should be obtained and included in the International Bunkers figures. UN estimates are available for many countries.

These adjustments to the energy balance can be quite significant and hence affect the calculation of greenhouse gases noticeably.

1.4 Carbon Dioxide Emissions from Energy

In this section the methodology for estimating CO_2 emissions from energy is discussed Carbon dioxide (CO_2) is the most common greenhouse gas produced by anthropogenic activities, accounting for about 60 per cent of the increase in radiative forcing since pre-industrial times (IPCC, 1992) By far the largest source of CO_2 emissions is from the oxidation of carbon when fossil fuels are burned, which accounts for 70-90 per cent of total anthropogenic CO_2 emissions. When fuels are burned, most carbon is emitted as CO_2 immediately during the combustion process. Some carbon is released as CO, CH_4, or non-methane hydrocarbons, which oxidise to CO_2 in the atmosphere within a period from a few days to 10-11 years. The IPCC methodology accounts for all of the carbon from these emissions in the total for CO_2 emissions. The other carbon-containing gases are also estimated and reported separately (see following sections for methodologies for estimating CH_4, CO, and NMVOCs).[6]

Fuel combustion is widely dispersed throughout most activities in national economies, and assembly of a complete record of the quantities of each fuel type consumed in each "end use" activity is a considerable task, which some countries have not yet completed. Fortunately, it is possible to obtain an accurate estimate of national CO_2 emissions by accounting for the carbon in fuels supplied to the economy. The supply of fuels is simple to record and is more likely to be available in many countries than detailed end use consumption statistics. For this reason, the IPCC Reference Approach for estimating emissions of CO_2 from fossil fuels is somewhat different than the approach used for other greenhouse gases. This is because CO_2 emissions depend mostly on the basic fuel characteristics rather than on technology or emission controls (as with gases such as NO_x or CO).

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[6] It is important to note, that there is an intentional double counting of carbon emitted from combustion. This format treats the non-CO_2 gases as a subset of CO_2 emissions and ensures that the CO_2 emission estimates reported by each country represent the entire amount of carbon that would eventually be present in the atmosphere as CO_2. The reasons for this double counting are discussed in the Introduction to the IPCC Guidelines, General Notes on the Guidelines.

The Reference Approach requires a careful accounting of fossil fuel production by energy type, carbon content of fossil fuels consumed, fossil fuel consumption by type, and production of products with long term carbon storage. In this respect the methodology for estimating CO_2 emissions represents more of a "top-down" approach compared to the "bottom-up" approach recommended for the other gases. This does not mean that a "bottom-up" approach used for other gases cannot also be followed for estimating CO_2 emissions. A method for estimating emissions with a "bottom-up" approach is briefly discussed later in this section. It is recommended that national experts who do detailed estimates of emissions of non-CO_2 gases should also apply CO_2 emission factors at this detailed level. In all cases, experts should estimate CO_2 emissions from fuel combustion using the IPCC Reference Approach also. This method provides the basis for international comparison, and all national CO_2 estimates should be reconciled with the results of this approach.

For all calculations of CO_2 emissions from fuel combustion, emissions are directly related to the amount of fuel consumed and the carbon content of the fuel. Coal contains close to twice the carbon of natural gas and roughly 25 per cent more than crude oil per unit of useful energy. A number of complicating factors need to be considered carefully:

- **Common Energy Units:** There is considerable variation in the energy content by weight of some fuels, especially coals. For comparison, all energy data must first be converted to a common energy unit (terajoules) before emission factors are applied.
- **Variations in Fuel Carbon:** For a given fuel type, even when quantified in energy units, the carbon per unit of useful energy varies. For example, not all coal types contain the same proportion of carbon. Generally speaking, the lower the quality of the coal (such as sub-bituminous coal and lignite), the higher the carbon emission factor (i.e., carbon per unit of energy).[7] There are similar carbon differences among the different types of liquids and gases.
- **Unoxidised Carbon:** When energy is consumed not all of the carbon in the fuel oxidizes to CO_2. Incomplete oxidation occurs due to inefficiencies in the combustion process that leave some of the carbon unburned or partially oxidised as soot or ash.
- **Stored Carbon:** Not all fuel supplied to an economy is burned for heat energy. Some is used as a raw material (or feedstock) for manufacture of products such as plastics, fertiliser, or in a non-energy use (e.g. bitumen for road construction, lubricants). In some cases, as in fertiliser production, the carbon from the fuels is oxidised quickly to CO_2 once applied and exposed to air. In other cases, as in road construction, the carbon is stored (or sequestered) in the product, sometimes for as long as centuries. The amounts stored for long periods are called *stored carbon* (or sequestered carbon), and should be deducted from the carbon emissions calculation. Estimation of stored carbon requires data on fuel used as feedstock and/or quantities of non-energy fuel products produced. The calculations are discussed within each of the alternative approaches presented in this section.
- **Bunker Fuels:** Bunker fuels refer to quantities of fuels used for international marine or aviation purposes. The IPCC methodology subtracts the quantities delivered to ships or aircraft *for international transport* from the fuel supply to the country. In this manner, the CO_2 emissions arising from the use of international bunkers are not included in the

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[7] The major exception to this relationship is anthracite or very hard coal, which typically has a higher carbon emission coefficient than bituminous coal.

national total. To simplify the preparation of global estimates, the emissions arising from bunker fuel use should be brought together in a separate table

- **Biomass Fuels:** Biomass fuels are included in the national energy and emissions accounts for completeness. These emissions should not be included in national CO_2 emissions from energy. If biomass is being regrown at roughly the same rate as it is being harvested on an annual basis, the net flux of CO_2 to the atmosphere is zero. If energy use, or any other factor, is causing a long term decline in the total carbon embodied in standing biomass (e.g. forests), this net release of carbon should be evident in the calculation of CO_2 emissions described in the *Land Use Change and Forestry* chapter.

All of the above issues are addressed within each of the approaches presented in the remainder of this section.

1.4.1 Approaches For Estimating CO_2 Emissions

The conceptual approach for estimating CO_2 emissions from energy consumption is straightforward. The basic calculations can be characterised as six steps that identify all of the factors necessary to calculate CO_2 emissions from energy consumption:

1 Estimating consumption of fuels by fuel product type

2 Converting the fuel data to a common energy unit (TJ) (if necessary)

3 Selecting carbon emission factors for each fuel product type and estimating the total carbon content of the fuels

4 Estimating the amount of carbon stored in products for long periods of time

5 Accounting for carbon not oxidised during combustion

6 Converting emissions as carbon to full molecular weight of CO_2

There are two basic approaches for estimating CO_2 emissions discussed in this document They vary primarily according to the level of detail at which these six steps are carried out The methods are

1 **The IPCC Reference Approach: Detailed Fuels.** The Detailed Fuels approach is the basic methodology recommended by the IPCC and requires information on several different types of energy products. This approach is sometimes referred to as "top-down" estimation since a country needs information only on the quantities of fuels produced indigenously, and those flowing into and out of the country through imports or exports. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

2 **Detailed Technology Based Calculation: "Bottom-Up" Method.** Most countries would ultimately like more detail on emissions of CO_2 by subsector than provided in the reference approach. This information is clearly necessary for evaluating policy options for reducing GHG emissions. In addition, if national experts are calculating emissions of non-CO_2 GHGs from fuel combustion, they are very likely working at a much finer level of energy use and technology detail. It is desirable to estimate CO_2 emissions and other gases at the same levels of detail for consistency purposes. The basic calculations can be applied at a very detailed level, including by sector and fuel types consumed in specific end-uses. This level of calculation is called "bottom-up" because it is very data-intensive, requiring a substantial amount of information about national energy consumption patterns in each sector of a nation's economy. Some of the additional complexities which must

be addressed at this level are discussed briefly at the end of this section. If national experts use this approach for CO_2 emissions, it is required that they also use the IPCC Reference Approach. Any significant differences between results at the two levels of detail should, if possible, be explained (see *Reporting Instructions*, Reporting the Inventory, Vol 1).

1.4.2 IPCC Reference Approach

The Reference Approach is based on an accounting of the carbon in fuels supplied to the economy. It involves the careful estimation of each country's production of fuels, imports and exports of fuels and refined products, deliveries of fuels for international bunkers, and changes in the stock levels for these fuels and products within the country. It uses a simple assumption: once carbon is brought into a national economy in fuel, it is either saved in some way (e.g., in increases of fuel stocks, stored in products, left unoxidised in ash) or it must be released to the atmosphere. It is not necessary to know exactly how the fuel was used or what intermediate transformations it underwent in order to calculate the carbon released.

Carbon accounting is based mainly on the total supply of primary fuels and the net quantities of secondary fuels brought into a country. Using these values, apparent consumption (i.e., energy supply) can be estimated. Once apparent consumption is estimated, subsequent steps account for carbon emission factors and other adjustments for the stored carbon, fraction oxidised, and other complications discussed in the introduction to this section.

ESTIMATE FUEL COMBUSTION

The first step of the IPCC Reference Approach is to estimate apparent consumption of fuels within the country. This requires a balance of primary fuels produced, plus imports, minus exports, minus international bunkers and minus net changes in stocks.[8] In this way carbon is "transferred" into the country from energy production and imports (adjusted for stock changes) and transferred out of the country through exports and international bunkers. In this accounting system for fuels supplied it is important to distinguish between *primary fuels*, which are fuels found in nature such as coal, crude oil, and natural gas, and *secondary fuels* or fuel products, such as gasoline and lubricants, which are derived from primary fuels.

To calculate the supply of fuels to the country, the following data are required for each fuel and inventory year:

- the amounts of primary fuels produced (production of secondary fuels and fuel products is excluded)
- the amounts of primary and secondary fuels and fuel products imported
- the amounts of primary and secondary fuels and fuel products exported

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[8] This approach is similar to, but not as detailed as, standard energy balance accounting. Energy balances, by their nature, are an attempt to reconcile supply (apparent consumption) with observed consumption where all the end-use sectors are separately identified. The Reference Approach includes only the data necessary to account for carbon flows into and out of a country. Therefore, the level of detail needed for this approach to CO_2 emissions estimation is not as great as for a complete national energy balance.

- the amounts of primary and secondary fuels used in international bunkers
- the net increases or decreases in stocks of fuels

The apparent consumption of primary fuels is, therefore, calculated from the above data as:

Apparent Consumption = Production + Imports - Exports
- International Bunkers - Stock Change.

An increase in stocks is a positive stock change. As this is subtracted in the equation, a positive stock change results in a decrease in apparent consumption A stock reduction is a negative stock change which, when subtracted in the equation, causes an increase in apparent consumption

Apparent consumption of secondary fuels should be added to primary apparent consumption. The production (or manufacture) of secondary fuels should be ignored in the calculations of apparent consumption. This is because the carbon in these fuels will already have been accounted for in the supply of primary fuels from which they were derived; for instance, the estimate for apparent consumption of crude oil already contains the carbon from which gasoline would be refined. However, information on production of some secondary fuel products is required in a later step to adjust for carbon stored in these products. Apparent consumption of secondary fuels is calculated as follows:

Apparent Consumption = Imports - Exports - International Bunkers
- Stock Change

Note that this calculation can result in negative numbers for apparent consumption This is a perfectly acceptable result for the purposes of this calculation since it indicates a net export or stock increase in the country *when domestic production of secondary fuels is not considered.*

Since carbon content typically varies by fuel type. data should be reported for detailed categories of fuel and product types as shown in Table 1-1 The table also illustrates the inputs and calculations recommended for the IPCC Reference Approach. The data are specified in the form available in the OECD/IEA *Energy Statistics* (1993*a* and 1993*c*)

TABLE 1-1
IPCC REFERENCE APPROACH
ENTRIES AND CALCULATIONS FOR STEPS (1) AND (2)

Fuel	(1) Production	(2) Imports	(3) Exports	(4) International Bunkers	(5) Stock Change	(6) Apparent Consumption[1]	(7) Conversion Factor	(8) Apparent Consumption (TJ)
A) Liquid Fossil						sum[2]		sum
Primary Fuels								
1) Crude Oil	input	input	input	NA	input	calc	input	calc
2) N. Gas Liquids	input	input	input	NA	input	calc	input	calc
Secondary Fuels / Products								
3) Gasoline	NA	input	input	input	input	calc	input	calc
4) Jet Kerosene	NA	input	input	input	input	calc	input	calc
5) Other Kerosene	NA	input	input	NA	input	calc	input	calc
6) Gas / Diesel Oil	NA	input	input	input	input	calc	input	calc
7) Residual Fuel Oil	NA	input	input	input	input	calc	input	calc
8) LPG	NA	input	input	NA	input	calc	input	calc
9) Ethane	NA	input	input	NA	input	calc	input	calc
10) Naphtha	NA	input	input	NA	input	calc	input	calc
11) Bitumen	NA	input	input	NA	input	calc	input	calc
12) Lubricants	NA	input	input	input	input	calc	input	calc
13) Petroleum Coke	NA	input	input	NA	input	calc	input	calc
14) Refinery Feedstocks	NA	input	input	NA	input	calc	input	calc
15) Other Oil	NA	input	input	NA	input	calc	input	calc
B) Solid Fossil						sum		sum
Primary Fuels								
16) Anthracite[6]	input	input	input	NA	input	calc	input	calc
17) Coking Coal	input	input	input	NA	input	calc	input[4]	calc
18) Other Bit. Coal	input	input	input	input	input	calc	input[4]	calc
19) Sub-bit. Coal	input	input	input	input	input	calc	input[4]	calc
20) Lignite	input	input	input	NA	input	calc	input[4]	calc
21) Peat	input	input	input	NA	input	calc	input	calc
Secondary Fuels								
22) BKB & Patent Fuel	NA	input	input	NA	input	calc	input	calc
23) Coke	NA	input	input	NA	input	calc	input	calc
C) Gaseous Fossil						sum		sum
24) Natural Gas (Dry)	input	input	input	NA	input	calc	input	calc
Total[3]						**sum**		**sum**
Information Entries								
Biomass Total						sum		sum
25) Solid Biomass	input	input	input	NA	input	calc	input	calc
26) Liquid Biomass	input	input	input	NA	input	calc	input	calc
27) Gas Biomass	input	input	input	NA	input	calc	input	calc

TABLE 1-1 (CONTINUED)
IPCC REFERENCE APPROACH
ENTRIES AND CALCULATIONS FOR STEPS (3) TO (6)

Fuel	(8) Apparent Consumption (TJ)	(9) Carbon Emission Factor[5] (t C/TJ)	(10) Carbon Content (Gg C)	(11) Carbon Stored (Gg C)	(12) Net Carbon Emissions (Gg C)	(13) Actual Carbon Emissions (Gg C)	(14) Actual CO_2 Emissions (Gg CO_2)
A) Liquid Fossil	sum		sum	sum	sum	sum	sum
Primary Fuels							
1) Crude Oil	calc	20.0	calc		calc	calc	calc
2) N. Gas Liquids	calc	15.2	calc		calc	calc	calc
Secondary Fuels / Products							
3) Gasoline	calc	18.9	calc		calc	calc	calc
4) Jet Kerosene	calc	19.5	calc		calc	calc	calc
5) Other Kerosene	calc	19.6	calc		calc	calc	calc
6) Gas / Diesel Oil	calc	20.2	calc		calc	calc	calc
7) Residual Fuel Oil	calc	21.1	calc		calc	calc	calc
8) LPG	calc	17.2	calc	Table 1-5	calc	calc	calc
9) Ethane	calc	16.8	calc		calc	calc	calc
10) Naphtha	calc	(20.0)	calc	Table 1-5	calc	calc	calc
11) Bitumen	calc	22.0	calc	Table 1-5	calc	calc	calc
12) Lubricants	calc	(20.0)	calc	Table 1-5	calc	calc	calc
13) Petroleum Coke	calc	27.5	calc		calc	calc	calc
14) Refinery Feedstocks	calc	(20.0)	calc		calc	calc	calc
15) Other Oil	calc	(20.0)	calc		calc	calc	calc
B) Solid Fossil	sum		sum	sum	sum	sum	sum
Primary Fuels							
16) Anthracite[6]	calc	26.8	calc		calc	calc	calc
17) Coking Coal	calc	25.8	calc	Table 1-5	calc	calc	calc
18) Other Bit. Coal	calc	25.8	calc		calc	calc	calc
19) Sub-bit. Coal	calc	26.2	calc		calc	calc	calc
20) Lignite	calc	27.6	calc		calc	calc	calc
21) Peat	calc	28.9	calc		calc	calc	calc
Secondary Fuels							
22) BKB & Patent Fuel	calc	(25.8)	calc		calc	calc	calc
23) Coke	calc	29.5	calc		calc	calc	calc
C) Gaseous Fossil	sum		sum	sum	sum	sum	sum
24) Natural Gas (Dry)	calc	15.3	calc	Table 1-5	calc	calc	calc
Total[3]	**sum**		**sum**	**sum**	**sum**	**sum**	**sum**
Information Entries							
Biomass Total	sum		sum		sum	sum	sum
25) Solid Biomass	calc	29.9	calc		calc	calc	calc
26) Liquid Biomass	calc	(20.0)	calc		calc	calc	calc
27) Gas Biomass[7]	calc	(30.6)	calc		calc	calc	calc

TABLE 1-1 (CONTINUED)
IPCC REFERENCE APPROACH
EMISSIONS FROM INTERNATIONAL BUNKERS (INTERNATIONAL MARINE AND AIR TRANSPORT)[8]

Fuel	(15) Quantities delivered[9]	(16) Conversion Factor (TJ/units)	(17) Quantities Delivered (TJ)	(18) Carbon Emission Factor (t C/TJ)	(19) Carbon Content (t C)	(20) Carbon Content (Gg C)
A) Solid Fossil						
Primary Fuels						
1) Other Bituminous Coal	input	input	calc	25.8	calc	calc
2) Sub-Bituminous Coal	input	input	calc	26.2	calc	calc
Liquid Fossil						
Secondary Fuels						
3) Gasoline	input	input	calc	18.9	calc	calc
4) Jet Kerosene	input	input	calc	19.5	calc	calc
5) Gas / Diesel Oil	input	input	calc	20.2	calc	calc
6) Residual Fuel Oil	input	input	calc	21.1	calc	calc
7) Lubricants	input	input	calc	(20.0)	calc	calc
Total			sum			

TABLE 1-1 (CONTINUED)
IPCC REFERENCE APPROACH
EMISSIONS FROM INTERNATIONAL BUNKERS (INTERNATIONAL MARINE AND AIR TRANSPORT)

Fuel	(21) Fraction of Carbon Stored	(22) Carbon Stored (Gg C)	(23) Net Carbon Emissions	(24) Actual Carbon Emissions (Gg C)	(25) Actual CO_2 Emissions (Gg CO_2)
A) Solid Fossil					
Primary Fuels					
1) Other Bituminous Coal	NA	calc	calc	calc	calc
2) Sub-Bituminous Coal	NA	calc	calc	calc	calc
Liquid Fossil					
Secondary Fuels					
3) Gasoline	NA	calc	calc	calc	calc
4) Jet Kerosene	NA	calc	calc	calc	calc
5) Gas / Diesel Oil	NA	calc	calc	calc	calc
6) Residual Fuel Oil	NA	calc	calc	calc	calc
7) Lubricants	0.5	calc	calc	calc	calc
Total					sum

TABLE 1-1 (CONTINUED)
EXPLANATORY NOTES

calc = value to be calculated. NA = not applicable

[1] Apparent Consumption = Production + Imports - Exports - International Bunkers - Stock Changes. A stock build is positive, a stock draw is negative

[2] Apparent Consumption for the aggregate categories of Liquid Fossil, Solid Fossil, Gaseous Fossil, and Biomass Fuels equal the sum of Apparent Consumption over the fuel types within the appropriate categories

[3] Total should include Liquid, Solid, and Gaseous Fossil Fuel subtotals only. Biomass subtotals are for reference purposes only and should not be included in the totals

[4] If data are in 10^3t, separate conversion factors are available for Production, Imports and Exports in Table 1-2. Each of these entries should be multiplied by the appropriate conversion factor. Then, the results should be summed to find Apparent Consumption in TJ (Col 8)

[5] If value is in parenthesis it is a default value until a fuel-specific CEF is determined

[6] If anthracite is not separately identifiable, include with Other Bituminous Coal

[7] Based on the assumption that 50 per cent of the carbon in the biomass is converted to methane

[8] The bunker emissions are not to be added to national totals

[9] See column 4 "International Bunkers"

CONVERT FUEL DATA TO A COMMON ENERGY UNIT (IF NECESSARY)

Fuel statistics should be expressed in energy units (in terajoules) to estimate CO_2 emissions accurately. In the OECD/IEA *Energy Statistics*, and in many other energy data compilations, production and consumption of solid and liquid fuels are specified in 10^3 tonnes (10^3 t). To convert tonnes to terajoules, net calorific values (NCV) must be applied. For unrefined fuels, energy content per tonne of fuel can vary widely from country to country. Default NCVs are provided for a number of countries based on IEA energy data. These values to convert from 10^3 tonnes to terajoules are in Table 1-2. Note that in some cases, particularly for coal, different NCVs are given for production, imports and exports in a given country. These can be used to convert each of these categories separately in the calculation of apparent consumption. For International bunkers and stock changes national experts can use a weighted average of the different NCVs, or use the one which represents the largest quantity of total apparent consumption for that coal type. For refined products the NCVs from 10^3 tonnes to terajoules do not normally vary greatly by country and global default values are provided in Table 1-3.[9]

National experts may use more detailed locally available NCVs. In this case, the values used should also be reported and documented. If original data are expressed in other energy units such as British thermal units (Btu's), million tons of oil equivalent (Mtoe), they should be converted to terajoules using standard conversion factors. If energy data are already available in terajoules, no conversion is necessary and column 7 of Table 1-1 can be ignored

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[9] Throughout the *Guidelines* net calorific values are used and expressed in SI units, for example TJ/kt. The term *Conversion Factor* has two uses. First, as net calorific value, to convert quantities expressed in natural units to energy units and, secondly as a scaling factor to convert one form of energy unit to another (e.g. Btus to GJ)

TABLE I-2
1990 COUNTRY-SPECIFIC NET CALORIFIC VALUES

(Terajoule per kilotonne)

	Albania	Algeria	Angola Cabinda	Argentina	Armenia	Azerbaijan	Bahrain	Bangladesh	Belarussia	Benin	Bolivi
OIL											
Crude Oil	41.45	43.29	42.75	42.29	-	42.08	42.71	42.16	42.08	42.58	43.31
NGL	-	43.29	-	42.50	-	-	42.71	42.71	-	-	43.31
COAL											
Hard Coal											
Production	-	25.75	-	24.70	-	-	-	-	-	-	.
Imports	27.21	25.75	-	30.14	18.58	18.58	-	20.93	25.54	-	.
Exports	-	-	-	24.70	18.58	18.58	-	-	25.54	-	.
Lignite and Sub-Bituminous Coal											
Production	9.84	-	-	-	-	-	-	-	-	-	.
Imports	-	-	-	-	14.65	14 65	-	-	14 65	-	.
Exports	9.84	-	-	-	14.65	14 65	-	-	14 65	-	.
Coal Products											
Patent Fuel/BKB	-	-	-	-	29 31	29.31	-	-	29 31	-	.
Coke	27.21	27.21	-	28.46	25.12	25.12	-	-	25 12	-	.

	Brazil	Brunei	Bulgaria	Cameroon	Chile	China	Colombia	Congo	Cuba	Cyprus	Czech Republi
OIL											
Crude Oil	42.54	42.75	42.62	42.45	42.91	42.62	42 24	42.91	41 16	42 48	41 78
NGL	45.22	42.75	-	-	42 87	-	41 87	-	-	-	.
COAL											
Hard Coal											
Production	18.42	-	24.70	-	28.43	20.52	27 21	-	-	-	24.40
Imports	30.56	-	24.70	-	28.43	20.52	-	-	25.75	25.75	23.92
Exports	-	-	-	-	-	20.52	27 21	-	-	-	27.98
Lignite and Sub-Bituminous Coal											
Production	-	-	7.03	-	17.17	-	-	-	-	-	12.26
Imports	-	-	-	-	-	-	-	-	-	-	.
Exports	-	-	-	-	-	-	-	-	-	-	15 26
Coal Products											
Patent Fuel/BKB	-	-	20.10	-	-	-	-	-	-	-	21 28
Coke	28.30	-	27.21	-	28.43	28.47	20.10	-	27 21	-	27.01

Crude oil conversion factors are based on weighted average production data.

The conversion factors are those used by the IEA in the construction of energy balances.

Source: OECD/IEA, 1993*a*.

TABLE I-2 (CONTINUED)
1990 COUNTRY-SPECIFIC NET CALORIFIC VALUES

(Terajoule per kilotonne)

	Ecuador	Egypt	Estonia	Ethiopia	Gabon	Georgia	Ghana	Guatemala	Hong Kong	Hungary	India
OIL											
Crude Oil	42.45	42.54	-	42.62	42.62	42.08	42.62	42.45	-	40.36	42.79
NGL	42.45	42.54	-	-	-	-	-	-	-	45.18	43.00
COAL											
Hard Coal											
Production	-	-	-	-	-	18.58	-	-	-	16.42	19.98
Imports	-	25.75	18.58	-	-	18.58	25.75	-	25.75	26.33	25.75
Exports	-	-	18.58	-	-	18.58	-	-	-	24.15	19.98
Lignite and Sub-Bituminous Coal											
Production	-	-	14.65	-	-	-	-	-	-	10.55	9.80
Imports	-	-	14.65	-	-	14.65	-	-	-	9.91	-
Exports	-	-	14.65	-	-	14.65	-	-	-	-	-
Coal Products											
Patent Fuel BKB	-	-	20.10	-	-	29.31	-	-	-	21.44	20.10
Coke	-	27.21	25.12	-	-	25.12	-	-	27.21	30.11	-

	Indonesia	Iran	Iraq	Israel	Ivory Coast	Jamaica	Jordan	Kazakhstan	Kenya	Kuwait	Kyrgyzstan
OIL											
Crude Oil	42.66	42.66	42.83	42.54	42.62	42.16	42.58	42.08	42.08	42.54	42.08
NGL	42.77	42.54	42.83	-	-	-	-	-	-	42.62	-
COAL											
Hard Coal											
Production	25.75	25.75	-	-	-	-	-	18.58	-	-	18.58
Imports	25.75	25.75	-	26.63	-	25.75	-	18.58	25.75	-	18.58
Exports	25.75	-	-	-	-	-	-	18.58	-	-	18.58
Lignite and Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	14.65	-	-	14.65
Imports	-	-	-	-	-	-	-	14.65	-	-	14.65
Exports	-	-	-	-	-	-	-	14.65	-	-	14.65
Coal Products											
Patent Fuel/BKB	-	-	-	-	-	-	-	29.31	-	-	29.31
Coke	27.21	-	-	-	-	-	-	25.12	-	-	25.12

Crude oil NCVs are based on weighted average production data

The NCVs are those used by the IEA in the construction of energy balances

Source OECD/IEA, 1993a

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC NET CALORIFIC VALUES

(Terajoule per kilotonne)

	Latvia	Leb-anon	Libya	Lithu-ania	Malaysia	Malta	Mexico	Moldova	Mor-occo	Mozam-bique	Myan-mar
OIL											
Crude Oil	-	42.16	43.00	42.08	42.71	-	42.35	-	43.00	-	42.24
NGL	-	-	-	-	43.12	-	46.81	-	-	-	42.71
COAL											
Hard Coal											
Production	-	-	-	-	25.75	-	24.72	-	23.45	25.75	25.75
Imports	18.58	-	-	18.59	25.75	25.75	30.18	18.58	27.63	25.75	25.75
Exports	18.58	-	-	18.59	25.75	-	22.41	18.58	-	-	-
Lignite and Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	-	-	-	8.37
Imports	14.65	-	-	14.65	-	-	-	14 65	-	-	-
Exports	14.65	-	-	14.65	-	-	-	14.65	-	-	-
Coal Products											
Patent Fuel/BKB	29.31	-	-	29.31	-	-	-	29.31	-	-	-
Coke	25.12	-	-	25.12	27.21	-	27.96	25.12	27 21	-	27.21

	Nepal	Neth. Antilles	Neutral Zone	Nigeria	North Korea	Oman	Paki-stan	Panama	Para-guay	Peru	Philip-pines
OIL											
Crude Oil	-	42.16	42.12	42.75	42.16	42.71	42.87	42 16	42 54	42.75	42.58
NGL	-	-	-	-	-	-	-	-	-	42.75	-
COAL											
Hard Coal											
Production	-	-	-	25.75	25.75	-	18.73	-	-	29.31	20.10
Imports	25.12	-	-	-	25.75	-	27.54	25.75	-	29.31	20.52
Exports	-	-	-	25.75	25.75	-	-	-	-	-	-
Lignite and Sub-Bituminous Coal											
Production	-	-	-	-	17.58	-	-	-	-	-	8.37
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Coal Products											
Patent Fuel/BKB	-	-	-	-	-	-	-	-	-	-	-
Coke	-	-	-	27.21	27.21	-	-	-	-	27.21	27.21

Crude oil NCVs are based on weighted average production data.

The NCVs are those used by the IEA in the construction of energy balances.

Source: OECD/IEA, 1993a.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC NET CALORIFIC VALUES

(Terajoule per kilotonne)

	Poland	Qatar	Romania	Russia	Saudi Arabia	Senegal	Sing-apore	South Africa	South Korea	Slovak Republic	Sri Lanka
OIL											
Crude Oil	41.27	42.87	40.65	42.08	42.54	42.62	42.71	44.13	42.71	41.78	42.16
NGL	-	43.00	-	-	42.62	-	-	-	-	-	-
COAL											
Hard Coal											
Production	22.95	-	16.33	18.58	-	-	-	25.09	19.26	-	-
Imports	29.41	-	25.12	18.58	-	-	-	-	27.21	23.92	25.75
Exports	25.09	-	-	18.58	-	-	-	25.09	-	-	-
Lignite and Sub-Bituminous Coal											
Production	8.36	-	7.24	14.65	-	-	-	-	-	12.26	-
Imports	-	-	7.24	14.65	-	-	-	-	-	-	-
Exports	9.00	-	-	14.65	-	-	-	-	-	15.26	-
Coal Products											
Patent Fuel/BKB	20.93	-	14.65	29.31	-	-	-	-	-	21.28	-
Coke	27.76	-	20.81	25.12	-	-	27.21	-	-	27.01	-

	Sudan	Syria	Taiwan	Tajik-istan	Tanz-ania	Thai-land	Trini-dad / Tobago	Tunisia	Turk-meni-stan	Ukraine	Utd Arab Emir-ates
OIL											
Crude Oil	42.62	42.04	41.4	42.08	42.62	42.62	42.24	43.12	42.08	42.08	42.62
NGL	-	-	-	-	-	46.85	-	43.12	-	-	-
COAL											
Hard Coal											
Production	-	-	25.96	18.58	25.75	-	-	-	-	21.59	-
Imports	-	-	27.42	18.58	-	26.38	-	25.75	18.58	25.54	-
Exports	-	-	-	18.58	-	-	-	-	18.58	21.59	-
Lignite and Sub-Bituminous Coal											
Production	-	-	-	-	-	12.14	-	-	-	14.65	-
Imports	-	-	-	14.65	-	-	-	-	14.65	14.65	-
Exports	-	-	-	14.65	-	-	-	-	14.65	14.65	-
Coal Products											
Patent Fuel/BKB	-	-	-	29.31	-	-	-	-	29.31	29.31	-
Coke	-	-	-	25.12	27.21	27.21	-	27.21	25.12	25.12	-

Crude NCVs are based on weighted average production data

The NCVs are those used by the IEA in the construction of energy balances

Source OECD/IEA, 1993*a*.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC NET CALORIFIC VALUES

(Terajoule per kilotonne)

	Uruguay	Uzbekistan	Venezuela	Viet Nam	Yemen	Former Yugoslavia	Zaire	Zambia	Zimbabwe
OIL									
Crude Oil	42.71	42.08	42.06	42.61	43.00	42.75	42.16	42.16	-
NGL	-	-	41.99	-	-	-	-	-	-
COAL									
Hard Coal									
Production	-	18.58	25.75	20.91	-	23.55	25.23	24.71	25.75
Imports	-	18.58	-	-	-	30.69	25.23	-	25 75
Exports	-	18.58	25.75	20.91	-	-	-	24.71	25.75
Lignite and Sub-Bituminous Coal									
Production	-	-	-	-	-	8 89	-	-	-
Imports	-	14.65	-	-	-	16.91	-	-	-
Exports	-	14 65	-	-	-	16.90	-	-	-
Coal Products									
Patent Fuel/BKB	-	29.31	-	-	-	20.10	29.31	-	-
Coke	-	25.12	27.21	27.21	-	26.90	27 21	-	27 21

Crude oil NCVs are based on weighted average production data.

The NCVs are those used by the IEA in the construction of energy balances

Source: OECD/IEA, 1993*a*

TABLE I-2 (CONTINUED)
1990 COUNTRY-SPECIFIC NET CALORIFIC VALUES

(Terajoule per kilotonne)

	Australia	Austria	Belgium	Canada	Denmark	Finland	France	Germany	Greece	Iceland	Ireland	Italy
OIL												
Crude Oil	43 21	42.75	42 75	42 79	42 71	42 66	42 75	42 75	42 75	-	42 83	42.75
NGL	45 22	45.22	-	45 22	-	-	45 22	-	45 22	-	-	45.22
Refinery Feedst	42 50	42 50	42 50	42 50	42 50	42 50	42 50	42 50	42 50	-	42 50	42.50
COAL												
Coking Coal												
Production	28 34	-	-	28 78	-	-	28 91	28 96	-	-	-	-
Imports	-	28 00	29 31	27 55	-	34 33	30 50	28 96	-	27 44	29 10	30 97
Exports	28 21	-	-	28 78	-	-	-	28 96	-	-	-	-
Other Bituminous Coal and Anthracite*												
Production	24 39	-	25 00	28 78	-	-	26 71	24 96	-	-	26 13	26.16
Imports	-	28 00	25 00	27 55	26 09	26 38	25 52	26 52	27 21	25 85	29 98	26 16
Exports	25 65	-	25 00	28 78	26 09	-	26 43	31 71	-	-	26 13	-
Sub-Bituminous Coal												
Production	17 87	-	18 06	17 38	-	-	-		-	-	-	-
Imports		-	-	-		-	-		-	-	-	-
Exports			18 20	-	-	-	-	-		-	-	-
Lignite												
Production	9 3	10 90		14 25	-	-	17 94	8 4	5 74	-	-	10 47
Imports	-	10 90	21 56		-	-	17 94	14 86	-	-	19 82	10 47
Exports	-	10 90	-	14 25		-	-	8 40	-	-	-	-
Coal Products												
Patent Fuel BKB	21 00	19 30	23 81	-	18 27	-	28 80	20 64	15 26	-	20 98	-
Coke	25 65	28 20	29 31	27 39	31 84	28 89	28 71	28 65	29 30	26 65	32 66	29 30

In IEA statistics Anthracite is combined with Other Bituminous Coal the NCVs given above reflect this combination

The NCVs for oil and coal are those used by the IEA in the construction of energy balances

The NCVs for coal product groupings listed are calculated from the values of their constituents

Source OECD IEA 1993b

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC NET CALORIFIC VALUES

(Terajoule per kilotonne)

	Japan	Luxembourg	Netherlands	NZ	Norway	Portugal	Spain	Sweden	Switzerland	Turkey	UK	USA
OIL												
Crude Oil	42.62	-	42.71	43.12	42.96	42.71	42.66	42.75	42.96	42.79	42.83	42.7
NGL	46.05	-	45.22	46.05	45.22	-	45.22	-	-	-	46.89	45.2
Refinery Feedst.	42.50	-	42.50	44.80	42.50	42.50	42.50	42.50	42.50	42.50	42.50	42.5
COAL												
Coking Coal												
Production	30.63	-	-	28.00	-	-	29.16	-	-	33 49	29 27	29.6
Imports	30.23	-	29.30	28.00	-	29.30	30.14	30.00	-	33.49	30.07	-
Exports	-	-	-	28 00	-	-	-	-	-	-	29 27	29.6
Other Bituminous Coal and Anthracite*												
Production	23.07	-	-	26.00	28.10	-	21.07	14.24	-	29 30	24 11	26.6
Imports	24.66	29.30	29.30	-	28.10	26.59	25.54	26.98	28.05	27 21	26 31	27.6
Exports	-	-	29 30	-	28 10	-	23 00	26.98	28 05	-	27 53	28.0
Sub-Bituminous Coal												
Production	-	-	-	21.30	-	17.16	11.35	-	-	-	-	19.4
Imports	-	-	-	-	-	-	11 35	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-	-
Lignite												
Production	-	-	-	14.10	-	-	7.84	-	-	9 63	-	14.1
Imports	-	20.03	20.00	-	-	-	-	8.37	-	12 56	-	-
Exports	-	-	20.00	-	-	-	-	-	-	-	-	14.1
Coal Products												
Patent Fuel/BKB	27.05	20.10	23.53	-	-	-	20.31	20.10	21.76	20.93	26.26	-
Coke	28.64	28.50	28.50	-	28.50	28.05	30.14	28.05	28.05	29.28	26.54	27.4

* In IEA statistics Anthracite is combined with Other Bituminous Coal – the NCVs given above reflect this combination.

The NCVs for oil and coal are those used by the IEA in the construction of energy balances.

The NCVs for coal product groupings listed are calculated from the values of their constituents.

Source OECD/IEA, 1993b.

TABLE 1-3
NET CALORIFIC VALUES FOR OTHER FUELS
($TJ/10^3$ tonnes)

Refined Petroleum Products	
Gasoline (aviation and auto)	44.80
Jet Kerosene	44.59
Other Kerosene	44.75
Gas/Diesel Oil	43.33
Residual Fuel Oil	40.19
LPG	47.31
Ethane	47.49
Naphtha	45.01
Bitumen	40.19
Lubricants	40.19
Petroleum Coke	40.19
Refinery Feedstocks	44.80
Other Oil Products	40.19
Other Products	
Coal Oils and Tars derived from Coking Coal	28.00
Source OECD IEA Paris 1993b	

SELECT CARBON EMISSION FACTORS AND ESTIMATE CARBON CONTENT

CO_2 emission estimates also need to consider that the amount of carbon per unit of energy (emission factor) may vary considerably both among and within primary fuel types:

- For natural gas, the carbon emission factor depends on the composition of the gas which, in its delivered state, is primarily methane, but can include small quantities of ethane, propane, butane, and heavier hydrocarbons. Natural gas flared at the production site will usually be "wet", i.e. containing far larger amounts of non-methane hydrocarbons. The carbon emission factor will be correspondingly different.
- For crude oil, Marland and Rotty (1984) suggest that the API gravity acts as an indicator of the carbon/hydrogen ratio. Carbon content per unit of energy is usually less for light refined products such as gasoline than for heavier products such as residual fuel oil.
- For coal, carbon emissions per tonne vary considerably depending on the coal's composition of carbon, hydrogen, sulphur, ash, oxygen, and nitrogen. While variability of carbon emissions on a mass basis can be considerable, carbon emissions per unit of energy (e.g., per terajoule) vary much less (with lower ranked coals such as sub-bituminous and lignites usually containing slightly more carbon than higher-ranked coals; anthracite is an exception since it typically contains more carbon than bituminous coal).

TABLE 1-4
CARBON EMISSION FACTORS FOR FUELS FROM DIFFERENT STUDIES

(t C/terajoule, net calorific value basis)[1]

Study	Anthracite	Bit. Coal	Sub-Bit. Coal	Lignite	Peat
Marland & Rotty (1984)		25.5[1]			
Marland & Pippin (1990)		25.4[1]			
Grubb (1989)	26.8[1]	25.8[1]		27.6[1]	28.9[1]
OECD (1991)		25.8[1,2]			

Study	Crude Oil	Gasoline	Kerosene	Gas/Diesel Oil	Fuel Oil	Natural Gas
Marland & Rotty (1984)	21.0[1]				15.2[1]	
Marland & Pippin (1990)	21.0[1]	19.4[1]	19.4[1]	19.9[1]	21.1[1,3]	15.3[1]
Grubb (1989)	20.0[1]	18.9[1]	19.5[1]	20.0[1]	21.1[1]	15.3[1]
OECD (1991)	20.0					15.3

[1] Values were originally based on gross calorific value; they were converted to net calorific value by assuming a 5 per cent difference in calorific value for coal and oil, and 10 per cent for natural gas. These percentage adjustments are the IEA assumptions on how to convert from gross to net calorific values.

[2] Average value for all coal: sub-bituminous through anthracite.

[3] Midpoint of range from 20.7 for light fuel oil (#4 fuel oil) to 21.6 for residual fuel oil (#6 fuel oil)

Estimates of carbon emission factors for fuels from several studies are summarised in Table 1-4.

One approach for estimating the carbon emission factors was presented in Marland and Rotty (1984). For natural gas, the carbon emission factor was based on the actual composition of dry natural gas. They sampled the composition of natural gas from 19 countries and then calculated a weighted average global gas composition, breaking the gas out into methane, ethane, propane, other hydrocarbons, CO_2, and other gases. The composition of the gas then determined both the calorific values of the gas and the carbon content. The carbon emission factor of the gas (t C/terajoule, using gross calorific values) was expressed using the following relationship:

$$\boxed{C_g = 13.708 + (0.0828 \times 10^{-3}) \times (H_v - 37{,}234)}$$

where C_g is the carbon emission factor of the gas in t C/terajoule (TJ) and H_v is the calorific value of the gas (gross calorific value, see OECD/IEA, 1993*b*) in kJ/cubic metre. The coefficients of the equation (13.708, 0.0828 x 10^{-3}, and 37,234) were estimated using regression analysis based on data from the 19 countries. The carbon content of oil was assumed to be a function of the API gravity: using an estimate of world average API gravity of 32.5° ± 2°, they estimated a composition of 85 ± 1 per cent carbon. Converting this to units of carbon per terajoule yielded an estimate of 21.0 t C/TJ on a net calorific value basis (assuming 42.62 terajoules per kilotonne, gross calorific value, as reported in Marland & Rotty, 1984). For coal, the literature suggested that the carbon content of coal was predominantly a function of the energy content (calorific value) and that the carbon content on a per tonne coal-equivalent basis was around 74.6 ± 2 per cent (Marland and Rotty 1984). The carbon emission factor was estimated to be 25.5 t C/TJ.

The approach used by M.J. Grubb (1989) to estimate carbon emission factors is very similar but based on more recent research. All carbon emission factors were originally reported on a gross calorific value basis, but are converted here to a net calorific value basis. He provides carbon factors for methane, ethane, propane, and butane and using data from Marland and Rotty (1984), estimates an average emission factor for natural gas of 15.3 t C/TJ ± 1 per cent. For oil and some refined petroleum products the estimates are based on data from the literature, as summarised in Table 1-4. The carbon emission factor of coal, excluding anthracite, was defined as:

$$\boxed{C_c = 32.15 - (0.234 \times H_v)}$$

where C_c is the carbon emission factor in t C/TJ and H_v is the gross calorific value of the coal when the calorific value is from 31 to 37 TJ/kilotonne on a dry mineral matter free (dmf) basis. Anthracites fall outside this range and a value of 26.8 t C/TJ is used.

Since the publication of the original OECD Background Document (OECD 1991), additional information has been made available on carbon emission factors. Key points from this new information are summarised below (all factors are in net calorific value):

- At an IPCC-sponsored workshop in October 1992 (IPCC/OECD, 1993), experts recommended several revised emission factors based on national inventory submissions to the OECD:

Oven or Gas Coke	29.5 t C/TJ
Natural Gas Liquids	15.2 t C/TJ
Petroleum Coke	27.5 t C/TJ
Refinery Gases	18.2 t C/TJ
Wood	29.9 t C/TJ
Blast Furnace Gas	66 t C/TJ
Coke Oven Gas[10]	13 t C/TJ
Bitumen	22 t C/TJ

- Of the country submissions received by the IPCC OECD programme to date only Canada has reported a specific emission factor for sub-bituminous coals. This was a value of 27.1 t C/TJ (Jaques, 1992). Detailed analysis conducted in the United States reported an average value of 26.2 t C/TJ (US DOE/EIA, 1992). Based on these two results, it appears that the value previously recommended in OECD (1991) should be lowered. Because the US analysis is documented in a detailed report, and US production of sub-bituminous coals is much higher than in Canada, the new recommended default value is 26.2 t C/TJ.
- The emission factor for ethane is derived from the net calorific value of 47,487 GJ/tonne taken from the American Petroleum Institute Research Project 44 of the National Bureau of Standards on the Collection, Analysis, Calculation and Compilation of Data on the Properties of Hydrocarbons.
- A number of countries have provided emission factors for jet kerosene including those reported in IPCC/OECD (1993) and more recent reports. Based on a weighted average of these values the recommended emission factor for jet kerosene is 19.5 t C/TJ.

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[10] This is the mid-point of a range of values.

The IPCC Reference Approach relies primarily on the emission factors from Grubb (1989), with additions from other studies as discussed above, to estimate total carbon content. The suggested carbon emission factors are listed in Table 1-1, Column 9. Table 1-1 also provides the calculations needed to estimate the total carbon content or that carbon which could potentially be released from the use of fuels. The basic methodology is:

$$\text{Total Carbon Content (Gg C)} = \sum \text{Apparent Energy Consumption (by fuel type in TJ)} \times \text{Carbon emission factor (by fuel type in t C/TJ)} \times 10^{-3}$$

Apparent consumption of the fuels is estimated in Table 1-1 (Column 6). The carbon emission factors for the fuels are average values based on net calorific value. This approach has been recommended by the IPCC because it explicitly treats each major fuel type differently according to its carbon emission factor. However, while carbon emission factors are available for most fuel types, some gaps in the data still remain. It is also possible that the default values provided here are not as accurate as country-specific factors that may be available. To the extent that other assumptions are used, countries should note the differences with the default values and provide documentation supporting the values used in the national inventory calculations.

ESTIMATE CARBON STORED IN PRODUCTS

After estimating the total carbon contained in the fuels, the next step is to estimate the amount of carbon from these fuels that is stored (or sequestered) in non-energy products and the portion of this carbon expected to oxidise over a long time period (e.g., greater than 20 years). All of the fossil fuels are used for non-energy purposes to some degree. Natural gas is used for ammonia production. LPGs are used for a number of purposes, including production of solvents and synthetic rubber. A wide variety of products are produced from oil refineries, including asphalt, naphthas, and lubricants. Coal is used to produce coke; two by-products of the coking process include oils and tars, which are used in the chemical industry.

Not all non-energy uses of fossil fuels, however, result in storage of carbon. For example, the carbon from natural gas used in ammonia production is oxidised quickly. Many products from the chemical and refining industries are burned or decompose within a few years, while the carbon in coke is oxidised when used. Several approaches for estimating the portion of carbon stored in products are reviewed in Box 1.

Box I
APPROACHES FOR ESTIMATING CARBON STORED IN PRODUCTS

The approach used by Marland and Rotty (1984) relied on historical data for determining non-energy applications and varied depending on fossil fuel type. For natural gas they assume that close to 1/3 of the carbon used for non-energy purposes (equivalent to 1 per cent of total carbon from natural gas production) does not oxidise over long periods of time. For oil products they assume that some portion of LPG, ethane, naphthas, asphalt, and lubricants does not oxidise quickly. Specifically, they assume that about 50 per cent of LPG and ethane from gas processing plants is sold for chemical and industrial uses and that 80 per cent of this amount, or 40 per cent of all LPG and ethane, goes into products that store the carbon. About 80 per cent of the carbon in naphthas is assumed to end up in products such as plastics, tires, and fabrics and oxidise slowly. All of the carbon in asphalt is assumed to remain unoxidised for long periods, while about 50 per cent of the carbon in lubricants is assumed to remained unoxidised. For coal they assume that on average 5.91 per cent of coal going to coke plants ends up as light oil and crude tar, with 75 per cent of the carbon in these products remaining unoxidised for long periods.

M.J. Grubb (1989) basically uses the Marland and Rotty (1984) approach, but suggests several changes, including higher estimates of methane losses during production and transportation of natural gas to market and a wide range of estimates concerning the fraction of carbon in refinery products that remain unoxidised. He does use Marland and Rotty's estimate of the amount of carbon in coal that does not oxidise, but also quantifies the amount of carbon emissions from SO_2 scrubbing (in which CO_2 is released during the chemical interactions in the desulphurisation process) using the formula: (% sulphur by weight) x (coal consumption) x 12/32

Okken and Kram (1990) introduce the concept of actual and potential emissions of CO_2 where potential emissions are defined as carbon that is stored in products from non-energy uses or by-products from combustion and actual emissions as all carbon from fuels that are emitted immediately or within a short period of time. Actual emissions plus potential emissions equal total carbon in the fuels. They assume that carbon from the following non-energy uses of fossil fuels oxidises quickly: fertiliser production (ammonia), lubricants, detergents, volatile organic solvents, etc. Carbon from the following non-energy uses of fossil fuels remains stored for long periods of time (in some cases, hundreds of years): plastics, rubber, bitumen, formaldehyde, and silicon carbide.

For the IPCC Reference Approach, the suggested formula for estimating carbon stored in products for each country is:

Total Carbon Stored (Gg C) =
Non-Energy Use (10^3 t)
x Conversion Factor (TJ/10^3 t)
x Emission Factor (t C/TJ)
x Fraction Carbon Stored
x 10^{-3}

This approach is slightly revised from the original methodology in OECD (1991). The main changes are expressing all activity data in terajoules rather than leaving all values in tonnes and using a corresponding emission factor rather than an assumption for percent carbon content. Most of the suggested categories conform to those used by Marland and Rotty (1984) and include naphthas, bitumen (asphalt), lubricants, LPG, and coal oils and tars. The data available from the UN reports (e.g., 1990) correspond to these categories, with the exception of coal oils and tars, which are not reported.

In addition, recent information has suggested some other modifications to the approach originally proposed in OECD (1991). These recommended modifications include:

- Carbon will be stored when naphtha is used as a feedstock in the petrochemical industry. However, in many countries naphtha is not always used as a feedstock. As the original methodology was based on total consumption of naphtha and not just that portion intended for use as a feedstock, the methodology has been changed to include only naphtha used as a feedstock. Also, available evidence from Western European countries indicates that about 75 per cent of naphtha used as feedstock is transformed into intermediate products in the petrochemical industry. The value of 75 per cent is slightly lower than the 80 per cent value originally assumed, which was based on US information only.
- Gas/Diesel oil may also be used as a feedstock. This category was not included originally in the methodology, but is added here. Evidence from Western European countries indicates that about half of the gas/diesel oil used as feedstock is transformed into intermediate products in the petrochemical industry.

The assumptions of 75 per cent for naphtha as a feedstock and 50 per cent for gas/diesel oil as a feedstock should be viewed as potential overestimates since not all of the carbon from the intermediate products will be stored. For example, carbon emissions may occur due to losses in the production of final products or incineration of final products. At this time these percentages can be used as the upper bound when determining stored carbon.

This suggested approach for estimating carbon stored in products is illustrated in Table 1-5. Whenever possible, countries should substitute assumptions that represent more accurately the practices within their own countries and provide documentation for these assumptions. The resulting estimates from Table 1-5 (Column 7) should be subtracted from carbon content of apparent consumption to determine net carbon emissions that could be oxidised. This calculation is done by entering the values from Table 1-5 (Column 7) for the relevant fuels/products into Table 1-1 (Column 11). In Table 1-1, carbon stored in products is subtracted from total carbon in the fuels ("carbon content") to get net carbon available for emission ("net carbon emissions").

TABLE 1-5
ESTIMATION OF CARBON STORED IN PRODUCTS

	1 Estimated Fuel Quantities[2]	2 Conversion Factor	3 Estimated Fuel Quantities[3]	4 Emission Factor	5 Carbon Content[4]	6 Fraction Carbon Stored	7 Carbon Stored[5]
Product/Fuel[1]	(Original Units)	TJ/Units	(TJ)	(t C/TJ)	(Gg C)		(Gg C)
Lubricants	calc	Table 1-3	calc	Table 1-1	calc	0.50	calc
Bitumen	calc	Table 1-3	calc	Table 1-1	calc	1.0	calc
Coal Oils and Tars from Coking Coal	calc[6]	Table 1-3	calc	Table 1-1[7]	calc	0.75	calc
Naphtha as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	0.75	calc
Gas/Diesel Oil as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	0.50	calc
Natural Gas as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	0.33	calc
LPG as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	0.80	calc

[1] This is only a partial list of products/fuels which accounts for the majority of carbon stored Where data are available for other fuels, the estimation of stored carbon is strongly encouraged.

[2] Either Apparent Consumption plus domestic (manufactured) production, or Feedstock Use

[3] Estimated Fuel Quantities in TJ (Col 3) equals Estimated Fuel Quantities (Col 1) times a Conversion Factor (Col 2).

[4] Carbon Content (Col 5) equals Estimated Fuel Quantities in TJ (Col 3) times an Emission Factor (Col 4)

[5] Carbon Stored (Col 7) equals Carbon Content (Col 5) times Fraction Carbon Stored (Col 6) divided by 10^3

[6] Use 6% of apparent consumption of Coking Coal

[7] Use the emission factor for coking coal (25 8 t C/TJ)

Currently the fraction carbon stored applied to the carbon content of the fuels used for product manufacture takes into account the release of carbon from the use or destruction of the products in the short term. The fraction is therefore lower than fraction of the carbon entering the products (see Box 1). The emissions resulting from the use or destruction of the products may occur in:

- industrial processes – both the production of non-fuel products from energy feedstocks, and the emissions from use of these products in industrial processes (e.g., oxidation of anodes made from petroleum coke during aluminium production).
- other end uses of products (e.g. lubricants oxidised in transportation)
- waste disposal – particularly incineration of plastics and other fossil fuel based products.

ESTIMATE CARBON OXIDISED DURING FUEL USE

As described earlier, not all carbon is oxidised during the combustion of fossil fuels. The amount of carbon that falls into this category is usually a small fraction of the total carbon, and a large portion of this carbon oxidises in the atmosphere shortly after combustion. Note that it is assumed that the carbon that remains unoxidised is stored indefinitely. Based on work by Marland and Rotty (1984), since 1991 the IPCC has been recommending that 1 per cent of the carbon in fossil fuels would remain unoxidised. This assumption was based on the following findings from Marland and Rotty for the amount unoxidised:

- For natural gas less than 1 per cent of the carbon in natural gas is unoxidised during combustion and remains as soot in the burner, stack, or in the environment.
- For oil 1.5% ±1% passes through the burners and is deposited in the environment without being oxidised. This estimate is based on 1976 US statistics of emissions of hydrocarbons and total suspended particulates.
- For coal 1% ±1% of carbon supplied to furnaces is discharged unoxidised, primarily in the ash.

However, several countries have commented that the amount of carbon remaining unoxidised is more variable than indicated by the 1 per cent assumption across all fuels. For example, it has been noted that the amount of unburnt carbon varies depending on several factors, including type of fuel consumed, type of combustion technology, age of the equipment, and operation and maintenance practices.

Information submitted by the Coal Industry Advisory Board of the OECD (Summers 1993), provided the following observations for coal combustion technologies:

- Unoxidised carbon from electric power stations in Australia averaged about 1 per cent. Test results from stoker-fired industrial boilers, however, were higher, with unoxidised carbon amounting to 1 to 12 per cent of total carbon with coals containing from 8 to 23 per cent ash. As average values, 2 per cent carbon loss was suggested for best practices, 5 per cent carbon loss for average practices, and 10 per cent carbon loss for worst practices. In those cases when coal is used in the commercial or residential sectors, carbon losses would be on the order of 5 to 10 per cent (Summers, 1993).
- In related work British Coal has provided information on the percentage of unburnt carbon for different coal combustion technologies:

Pulverised Coal	1.6%
Travelling Grate Stoker	2.7-5.4%
Underfeed Stoker	4.0-6.6%
Domestic Open Fire	0.6-1.2%
Shallow Bed AFBC	Up to 4.0%
PFBC/CFBC[11]	3.0%

- Evaluations at natural gas-fired boiler installations indicate that combustion efficiency is often 99.9 per cent at units reasonably well-maintained.

It is clear from the available information that a single global default assumption of 1 per cent unoxidised carbon is not always accurate. While some additional information is available to refine the assumptions for this portion of the methodology, most of the new information requires some level of detail on the type of technology in which the fuel is combusted or information on which sector is consuming the fuel. For this approach, the methodology only requires data on the amount of fuels consumed in a country, not data by technology type or sector of the economy. As a result, based on the information available at this point, the default values presented in Table 1-6 are recommended for the percentage of carbon oxidised during combustion by fuel. It should be recognised that the value for coal is highly variable based on fuel quality and technology types. National experts are encouraged to vary this assumption if they have data on these factors, suggesting that different average values for their countries are appropriate. It is clear from the information available at this time that additional research should be conducted on this topic.

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[11] AFBC = Advanced Fluidised Bed Combustion
CFBC = Circulating Fluidised Bed Combustion
PFBC = Pressurised Fluidised Bed Combustion

TABLE 1-6
FRACTION OF CARBON OXIDISED
RECOMMENDED DEFAULT ASSUMPTIONS

Coal[1]	0.98
Oil and Oil Products	0.99
Gas	0.995
Peat for electricity generation[2]	0.99

[1] This figure is a global average but varies for different types of coal, and can be as low as 0.91

[2] Peat used in households may be much lower

ESTIMATE TOTAL CARBON DIOXIDE EMISSIONS FROM FUEL COMBUSTION

Net carbon emissions (column 12 in Table 1-1) is then multiplied by the fraction of carbon oxidised to give actual carbon emissions (column 13 of Table 1-1), and then summed across all fuel types, to determine the total amount of carbon oxidised from the combustion of fuel. To express the results as carbon dioxide (CO_2), total carbon oxidised should be multiplied by the molecular weight ratio of CO_2 to C (44/12) to find total carbon dioxide emitted from fuel combustion.

1.4.3 Detailed Technology-Based Calculations

This section briefly discusses procedures already used by some countries for estimating CO_2 emissions from fuel consumption at a more detailed and data-intensive level. This is a "bottom-up" approach in that emissions are estimated by sector of economic activity and/or by type of technology in which the fuel is consumed. The results for a wide range of end-uses and transformation activities must be summed to arrive at total national emissions. This discussion does not represent step by step guidance, but rather an initial discussion that raises some issues which should be considered.

A greater level of detail than is provided by the IPCC Reference Approach may ultimately be needed by most, if not all, countries participating in international climate change discussions. Such detail is important for analysis of policy options for reducing emissions, as these are frequently related to specific end uses rather than aggregate fuel use. As discussed in the next three sections, a more detailed approach is needed to estimate credibly emissions of several non-CO_2 greenhouse gases from fuel combustion. Countries that have developed detailed energy and technology data for calculating emissions of NO_x, CO and other gases will wish to ensure that CO_2 emissions estimates are consistent and comparable. For this reason they may wish to utilise a detailed approach for CO_2 along with their calculations for other GHG's from energy. The paragraphs below will assist them by identifying some of the calculation issues which will have to be resolved.

The very detailed technology-based approach does not provide a completely satisfactory result for two reasons. First it requires large amounts of data and time. Second, even the most detailed technology-based estimates produced in some countries do not always carry with them the data necessary to connect emissions with economic subsectors of interest. In the future, the IPCC/OECD programme plans to provide more guidance on applying a more detailed sectoral approach. This will be less detailed than the Technology-Based estimates but will still provide emissions broken down by economic sectors and subsectors of concern.

The detailed technology-based calculations should be essentially the same as those carried out in the Reference Approach, but should be carried out at a finer level of resolution.

The formula is:

carbon emissions

=

Σ fuel consumption (actual now rather than apparent) expressed in energy units (TJ) at the level of transformation or end use subsector and possibly by specific technology/process

x carbon emission factor

- carbon stored

x fraction oxidised

Stored carbon would be calculated as is done in the reference approach although this, too, may be done at a finer level of product/process detail.

The calculations resemble those used to estimate emissions other than CO_2 from stationary and mobile source combustion. The methodologies for estimating emissions from these sources are discussed in detail in the following three sections. The Reference Approach for CO_2 only requires data by fuel type at the national level, but for the detailed calculations, national experts would be required to provide much more detailed data on energy consumption patterns. Once countries have obtained the activity data required for estimating detailed "bottom-up" inventories of NO_x, CO, etc., from combustion in stationary and mobile sources (i.e., fuel consumption data by sector by technology type), they can also estimate CO_2 emissions as part of the inventory estimates for these other gases. The amount of fuel consumed for each disaggregated category can be multiplied by an appropriate emission factor to determine the carbon content of fuels combusted. The fraction oxidised must also be accounted for in each category.

Countries calculating their emissions at the detailed technology-based level should cross-check their carbon emission estimates by also using the Reference Approach, and reconcile any major differences. The most important value of the Reference Approach is that it provides a simple, transparent and verifiable means of accounting for all of the carbon in fuels which could potentially be emitted to the atmosphere. Because of the complexities of energy data and accounting, it may not always be the case that adding up the fuel used from detailed data sets will account for all of the carbon in original fuels.

ESTIMATING FUEL COMBUSTION BY SECTOR AND TECHNOLOGY TYPE

In this approach countries would estimate fuel consumption for at least the same fuel categories specified for the Reference Approach. A few additional fuel types such as Blast Furnace Gas and Refinery Gas may need to be added to account for all of the fuels in their end-use form. The concept of "apparent consumption" used in the Reference Approach allows users to ignore some of the details in fuel transformations. For example, while we know that in fact crude oil is not actually consumed as an end use fuel, we also know that all the carbon in the original crude oil is emitted to the atmosphere unless: a) it is converted to a non-fuel product (stored carbon), or b) it is incompletely oxidised and remains as ash at a combustion or transformation step.

When working at the detailed level, countries would estimate actual fuel consumption for these fuel categories rather than apparent consumption. Moreover, rather than determining total national fuel consumption for these categories, a country would need to determine the amount of fuel consumed in each sector in order to estimate emissions for each sector of the economy. It may be necessary to account for actual consumption of specific fuels in various end use subcategories, further broken down by specific processes and technologies. Then one needs to work backwards to arrive at the total amounts of carbon supplied as fuels to an economy.

A major area of difficulty in this process is accounting for the carbon released in transformation of energy from one form to another. The largest emissions from this subsector are associated with electric power generation, in which fossil fuels are converted into electricity. These emissions are treated exactly like end use fuel combustion emissions in most detailed inventories so this component should be relatively straightforward.

Other transformations such as the refining of crude oil into oil products and the production of coke from coal can be more complicated and may be difficult to account for fully in the "bottom-up" approach. A simple input-output analysis may be helpful in accounting for the carbon releases during transformation steps. For example, a refinery (or all refineries of a specific type) is a complex set of processes, but can be considered as a single box. Total carbon in the form of crude oil (and possibly other input energy forms) can be estimated. Total carbon out of the box in the form of secondary fuels or fuel products can be estimated. Any carbon disposed of in the form of wastes (such as ash), which represent stable long term storage, can be estimated. Any carbon not accounted for in one of these output forms must be assumed to have oxidised as a result of the transformation process. For gases other than carbon dioxide recourse to data on which fuels are combusted and their conditions of combustion are essential for a proper analysis of non-CO_2 emissions from the transformation sector.

Primary fuels that are not combusted directly would thus not appear in end use combustion, although they may be considered as input to the input-output analysis of transformation steps. In both transformation and in some end use applications, the detailed technology-based level will require explicit accounting of some intermediate products, such as blast furnace gas - which can be ignored in the Reference Approach. At a minimum it is recommended that countries using the Detailed Technology-Based Approach report emissions by the major fuel-consuming sectors defined in *Volume 1: Reporting Instructions.*

- Energy and Transformation Industries
- Industry
- Transport

- Small Combustion
- Other
- Biomass Burned for Energy (unallocated to any of the other sectors listed above)

Within each consuming sector emission estimates could also be developed according to the technology type in which the fuel was consumed. The later sections on stationary and mobile source combustion list possible technology source categories that could be estimated. Additional work needs to be done to define a full set of appropriate technology categories.

CONVERTING TO A COMMON ENERGY UNIT

This is handled exactly as in the Reference Approach. Wherever detailed fuel consumption data are collected in original physical units such as 10^3 tonnes or other energy units such as tonnes of oil equivalent (toe), they should be converted to terajoules (TJ) using the same conversion procedures discussed in the Reference Approach.

CARBON EMISSION FACTORS

Once fuel consumption data are provided in TJ for the relevant sectors and/or technology types, these consumption estimates can be multiplied by the appropriate carbon emission factors to determine carbon content in tonnes of carbon (t C). The default emission factors are the same as those used in the Reference Approach since the carbon content of specific fuel types does not change by sector or technology application. For example, if bituminous coal is used in an industrial boiler, a country could use the same emission factor for bituminous coal it would select under the Reference Approach. A country may vary the emission factor from one application to another if it has reason to believe that the fuel qualities may differ. If it is known that bituminous coal consumed in the industrial sector has significantly different fuel qualities than the average bituminous coal consumed in the country, then a country may wish to use an alternative emission factor. Unless such information is available, however, the default emission factors used in the Reference Approach are acceptable.

These factors are provided again in the following sections on stationary and mobile source combustion. In some cases the factors are also converted to different forms (e.g. t CO_2/TJ, g CO_2/km) where these are more appropriate for specific end uses. Countries using alternative emission factors should note these differences and report the reasons for using an alternative factor. As in the IPCC Reference Approach, CO_2 emissions from international bunker fuels and biomass fuels are for informational purposes only, and should not be added to overall totals. They should be shown as separate totals when reporting.

CARBON STORED

Calculations of stored carbon for countries choosing to use a Detailed Technology-Based Approach should be more straightforward since the country would already be collecting fuel consumption data at a disaggregated level. The methodology for calculating stored carbon (non-fuel uses) is the same as the procedures used in the Reference Approach. That is, fuel quantities for which carbon may be stored should be estimated, then converted to TJ, and multiplied by the carbon emission factor to determine the carbon content of the fuel. Then it should be multiplied by the fraction of carbon stored to determine the carbon stored for each fuel. It may be that national experts working at a detailed technology-based level may account for non-fuel uses for a more detailed level of products and processes. In this case, default factors may not apply, and fractions of carbon actually stored and in some cases carbon emission factors will have to be supplied by the national experts.

The adjustments for stored carbon (deductions of Gg C stored) would have to be made to the appropriate sector for which emissions are being estimated. In most cases, these adjustments are made to emission estimates from the industrial sector since most uses for which potential storage of carbon have been identified are from this sector. The Detailed Technology Based Approach should result in more accurate estimates of stored carbon than the Reference Approach. Nevertheless, it is requested that national results be reconciled with results obtained from use of the Reference Approach, and therefore to explain differences in stored carbon estimates.

ADJUSTMENTS FOR CARBON UNOXIDISED

As discussed above under the Reference Approach, the amount of carbon that may remain unoxidised from combustion activities can vary for many reasons, including type of fuel consumed, type of combustion technology, age of the equipment, and operation and maintenance practices. Since the Detailed Technology-Based Approach relies on more disaggregated fuel consumption data, it is possible to specify the assumptions for unoxidised carbon by application. Unless other data are available, countries should use as default values the assumptions recommended in the Reference Approach: 2 per cent of carbon in fuel consumed is unoxidised for coal, 1 per cent for oil-derived fuels, 0.5 per cent for natural gas and 1 per cent for peat used for electricity generation. In addition, the following assumptions (from Summers, 1993) are recommended:

- For stoker-fired industrial boilers an average value for carbon unoxidised is 5 per cent. If countries believe that their operation and maintenance procedures achieve maximum efficiency, a 2 per cent carbon loss is suggested. If these procedures are believed to lead to very poor efficiency, then a 10 per cent carbon loss is recommended.
- In those cases when coal is used in the commercial or residential sectors, the assumption for unoxidised carbon should be 5 per cent.

Clearly, much additional research needs to be done in this area. These adjustments are suggested as initial default values. As more work is done, countries are encouraged to report any additional information they may have to refine understanding of the amount of carbon unoxidised in various applications.

CONVERTING TO CO_2 EMISSIONS

This is also similar to the Reference Approach. For some end use categories emission factors may be provided directly as t CO_2/TJ. Wherever emissions have been calculated as carbon, they must be expressed as carbon dioxide (CO_2). To convert to CO_2, total carbon oxidised should be multiplied by the molecular weight ratio of CO_2 to C (44/12) to find the total carbon dioxide.

1.5 Greenhouse Gas Emissions from Stationary Sources

1.5.1 Overview

This section discusses greenhouse gas emissions (CO_2, NO_x, N_2O, CO, CH_4, and NMVOCs) from energy consumption in stationary combustion plants. The section focuses on emissions from the combustion of commercial fuels, which include virtually all fossil fuels and biomass fuels traded commercially and used in large combustion plants. Emissions from combustion of biomass are estimated in exactly the same manner as fossil fuel combustion emissions, except for CO_2 emissions[12]. A large share of total global biomass fuel consumption, however, is not accounted for in commercial energy statistics. GHG emissions from this "traditional" biomass fuel use, primarily in developing countries, are calculated differently and discussed in the section of this chapter on the burning of biomass fuels.

Emissions of non-CO_2 greenhouse gases across activities (sectors and subsectors) will depend upon fuel, technology type, and pollution control policies. Emissions will also vary with the size and vintage of the combustion technology, its maintenance, and its operation. As discussed in the previous section, CO_2 emissions are not technology-dependent, although these emissions can be classified by technology using a "bottom-up" approach, as described in this section.

In addition to CO_2, most of a country's NO_x emissions arise from stationary fuel combustion. As defined here (i.e., excluding "traditional" biomass), this category generally contributes a smaller but still significant share of national emissions of CO and NMVOC, and, to a lesser extent, to total N_2O and CH_4.These two gases are nonetheless discussed in some detail because of their priority status within the IPCC/OECD programme.

Organisation of the section

The next subsection provides a general discussion of the emissions calculation method common to the estimation of all GHGs from detailed fuel combustion data. This includes discussion of data needed including extra data required as discussed earlier in the subsection concerning the Detailed Technology-Based Calculations, and highlights the importance of fuel- and technology-specific emission factors in this approach. The following subsection provides a series of tables of representative emission factors and their ranges for different technologies.

Two additional subsections discuss each of the relevant gases. This discussion is presented in two parts – dealing with direct GHGs (CO_2, N_2O and CH_4), and indirect GHGs (NO_x, CO, and NMVOC) respectively. The priority area of work for the IPCC/OECD programme in the initial stages was to develop methodologies for direct GHGs. Thus, improvements in methods for these gases are discussed in some detail. For CO_2, further discussion is provided to assist national experts who wish to do these calculations at a "bottom-up" level of detail. N_2O and CH_4 from stationary combustion are relatively minor as shares of total emissions. Nonetheless, as priority gases, a review of recent research is included for each.

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[12] CO_2 emissions resulting from biomass fuel consumption should not be included in national energy emission totals because: (1) biomass fuels may have been produced on a sustainable basis, particularly for commercial consumers, such that no net increase in CO_2 occurs, or (2) production of CO_2 due to extraction of biomass fuels from existing stocks on a non-sustainable basis would be captured as part of emissions which are calculated as described in the Land Use Change and Forestry chapter in this manual. The IPCC method recommends that countries estimate CO_2 emissions from biomass fuel consumption and report this as an information item.

For indirect gases, the IPCC/OECD programme has not carried out any original methods development work. However, these gases are traditional air pollutants, as well as indirect GHGs, and have been the focus of a great deal of ongoing work outside the IPCC/OECD programme. The discussion of these gases focuses on identification of comprehensive, up-to-date references which have been published by other inventory programmes, including CORINAIR and programmes of individual countries.

Finally, the last subsection discusses some priorities for future work.

1.5.2 Recommended Methodology

General Method

Estimation of emissions from stationary sources can be described using the following basic formula:

$$\boxed{\text{Emissions} = \sum (EF_{abc} \times \text{Activity}_{abc})}$$

where:

EF = Emission Factor (kg/TJ);

Activity = Energy Input (TJ);

a = Fuel type;

b = Sector-activity; and

c = Technology type.

Total emission for a particular nation is the sum across activities, technologies and fuels of the individual estimates.

Emission estimation is based on at least three distinct sets of assumptions or data: 1) emission factors; 2) energy activities; and 3) relative share of technologies in each of the main energy activities. Sources of the emission factors and energy activities data that are relevant internationally are described briefly below and suggestions on appropriate use of such data are made.

Technology share or technology splits for each of the various energy activities are needed at least on a national level for non-CO_2 greenhouse gas estimation since emission levels are affected by the technology type. Unfortunately, there are no complete international sources of data on technology splits and, as a result, each nation will need to develop its own technology splits for each energy activity.

The main steps in the inventory method can be summarised as follows:

1 Determine source of, and the form of, the best available, internationally verifiable, national (or sub-national) energy activity data;

2 Based on a survey of national energy activities, determine the main categories of emission factors;

3 Compile best available emission factor data for the country, preferably from national sources. If no national sources are available, select from the options described here. Selection among the options should be based on the similarity of the country to the source of original measurements for types of technology and operating conditions across main energy activities. The selection should also consider the extent to which control technologies may be in place and requires the ability to clearly separate and understand control policy assumptions that may be embedded in the emission factor data.

4 Based on the form of the selected emission factors, identify the technology categories to be used in the national inventory;[13]

5 Using these assumptions on technology categories, develop estimates for each main activity of each of the greenhouse gases.

6 Sum the individual activity estimates to arrive at the national inventory total for each of the greenhouse gases.

Data Needs

A considerable amount of detailed and specialised data is required to construct a national inventory of GHGs from stationary fuel combustion. At least the following types of data are needed:

- **Energy Activity Data**

Energy data sources are discussed under the heading Energy Activity Data within section 1.1. The same basic energy information is needed in estimating other GHGs from fuel combustion.

International sources or locally available sources of energy activity data can be used, provided that the definitions and formats specified in the IPCC methodology are used to ensure comparability and transparency. However, national sources will be needed for activity data relating to specific technologies. It should be noted, that in many countries, energy consumption data may be available in truly "bottom-up" data collection efforts, associated with major programmes to develop detailed emissions estimates. That is, energy consumption data may be collected, along with technology information on a source by source, region by region, or other disaggregated level. It is, of course, highly desirable to have actual data on fuel use by technology type, rather than having to allocate down from national statistics. It is important, however, in this situation, to reconcile total national energy accounts with "bottom-up" fuel use data carefully, to ensure that all fuel combustion is being accounted for and none is double-counted.

- **Technology Splits for Energy Data**

National data or assumptions on the technology shares of each of the main source sector categories which have been identified as important in each country are necessary to create the linkage between national energy balances and the emission factors. Again, this may be based on "bottom-up" data collection at as detailed a level as individual sources, or it may be more of a "top-down" allocation based on statistical sampling, or engineering judgement. The objective is to match up fuel use, by fuel type, with specific technologies or classes of technologies, for which credible emission factors for non-CO_2 gases can be provided.

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[13] This may also require assumptions about the control technologies in place.

- **Emission Factor Data**

Emission factors represent the average emission performance of similar technologies. Emission factors for all non-CO_2 greenhouse gases from combustion activities vary to lesser or greater degrees with:

- fuel type;
- technology;
- operating conditions; and
- maintenance and vintage of technology.

Precise emission factors for gases other than CO_2 are therefore usually technology specific, but may still represent a wide distribution of possible values because of the influence of the other three factors above. When available, the standard deviation of the emission factor should be used to show the range of possible emission factors, and hence emissions, for each particular energy activity.[14]

There already exists a considerable body of literature and other data bases on emission factors, particularly for the indirect GHGs (NO_x, CO, and NMVOC) which are of great interest as local and regional air pollutants, in addition to their global effect on radiative forcing of the atmosphere. In some cases, basic emission factors for specific technology types, may need adjustment for the effects of control technologies. Accounting for controls is particularly critical to estimation of emissions from large stationary sources in OECD countries, but probably has a minor effect on emission estimates for the rest of the world since control technologies are not typically used in these countries (see OECD/IEA, 1991).

More detail on current emission factors and references is presented in the gas-by-gas discussions which follow after the next section.

1.5.3 Illustrative Emission Factor Data

Some tables of representative emission factors for No_x,[15] CO, CH_4, N_2O, and NMVOCs by main technology and fuel types (based on Radian, 1990) were presented in the previous preliminary methodology manual (OECD, 1991) distributed by the IPCC. This information is still useful in showing the range and variation of sources and emission rates, and it is reproduced in Tables 1-7 to 1-11 for the major categories.[16] All factors are expressed on a kilograms per terajoule of energy input basis (unless stated otherwise) and are stated on a full molecular weight basis. These data are taken from Radian (1990) and show uncontrolled emission factors for each of the technologies indicated. These emission factor data therefore do not include the level of control technology that might be in place in some countries. For instance, for use in countries where control policies have significantly influenced the emission profile, either the individual factors or the final estimate will need to be adjusted.

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[14] Unfortunately, the standard deviation of emission factors is rarely reported with emission factor data. One study shows that when considered, variation of emission factors within an energy activity vary widely, from 20 to more than 50 per cent (Eggleston and McInnes, 1987).

[15] The convention in this document is that NO_x emissions from fossil fuel combustion are expressed on a full molecular basis assuming that all NO_x emissions are emitted as NO_2.

[16] Little reliable information on N_2O and NMVOCs emission factors was available at the time these tables were developed. Some more recent information is presented for reference later in this section.

It may be necessary to make adjustments to "raw" emission estimates to account for control technologies in place. Alternative control technologies, with representative percentage reductions, are shown in Tables 1-12 to 1- 15 (Radian, 1990) for the main control technologies applicable to each sector. These tables reflect technologies in use for large stationary sources in OECD countries. Preliminary indications are that, in the rest of the world, control technologies are not typically used (see OECD/IEA, 1991). These data should be used in combination with the uncontrolled emission factors to develop a "net" representative emission factor for each of the technologies to be characterised in the national emission profile; alternatively, the emission estimate for each technology could be adjusted downward according to the indicated percentage reduction and the estimated penetration of the control technology.

Table 1-16 provides the fuel property assumptions upon which the Radian data are based.

The emission factor data in these tables are provided primarily for illustrative purposes. These factors could be used as a starting point or for comparison by national experts working on detailed "bottom-up" inventories. More detail on current emission factors and references is presented in the gas-by-gas discussions in the next two sections.

TABLE 1-7
UTILITY BOILER SOURCE PERFORMANCE

	Emission Factors (kg/TJ energy input)[1]				
Source	CO	CH_4	NO_x	N_2O	NMVOCs
Natural Gas - Boilers	19	0.1	267	N/A	N/A
Gas Turbine Combined Cycle	32	6.1	187	N/A	N/A
Gas Turbine Simple Cycle	32	5.9	188	N/A	N/A
Residual Oil Boilers	15	0.7	201	N/A	N/A
Distillate Oil Boilers	15	0.03	68	N/A	N/A
Shale Oil Boilers	15	0.7	201	N/A	N/A
MSW - Mass Feed[2]	98	N/A	140	N/A	N/A
Coal - Spreader Stoker	121	0.7	326	0.8	N/A
Coal - Fluidised Bed Combined Cycle	N/A	0.6	N/A	N/A	N/A
Coal - Fluidised Bed	N/A	0.6	255	N/A	N/A
Coal - Pulverised Coal	14	0.6	857	0.8	N/A
Coal - Tangentially Fired	14	0.6	330	0.8	N/A
Coal - Pulverised Coal Wall Fired	14	0.6	461	0.8	N/A
Wood-Fired Boilers[2]	1,473	18	112	N/A	N/A

[1] Values were originally based on gross calorific value; they were converted to net calorific value by assuming that net calorific values were 5 per cent lower than gross calorific values for coal and oil, and 10 per cent lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net calorific values.

[2] Emission factors were adjusted to net calorific value assuming a 5 per cent difference in energy content between net calorific value and gross calorific value.

Source: Radian, 1990.

TABLE 1-8
INDUSTRIAL BOILER PERFORMANCE

	Emission Factors (kg/TJ energy input)[1]				
Source	CO	CH_4	NO_x	N_2O	NMVOCs
Coal-Fired Boilers	93	2.4	329	N/A	N/A
Residual Oil-Fired Boilers	15	2.9	161	N/A	N/A
Natural Gas-Fired Boilers	17	1.4	67	N/A	N/A
Wood-Fired Boilers[2]	1,504	15	115	N/A	N/A
Bagasse/Agricultural Waste-Fired Boilers[2]	1,706	N/A	88	N/A	N/A
MSW - Mass burn[2]	96	N/A	140	N/A	N/A
MSW - Small Modular[2]	19	N/A	139	N/A	N/A

[1] Values were originally based on gross calorific value; they were converted to net calorific value by assuming that net calorific values were 5 per cent lower than gross calorific values for coal and oil, and 10 per cent lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net calorific values.

[2] Emission factors were adjusted to net calorific value assuming a 5 per cent difference in energy content between net calorific value and gross calorific value.

Source: Radian, 1990.

TABLE 1-9
KILNS, OVENS, AND DRYERS SOURCE PERFORMANCE

		Emission Factors (kg/TJ energy input)[1]				
Industry	Source	CO	CH_4	NO_x	N_2O	NMVOCs
Cement, Lime	Kilns - Natural Gas	83	1.1	1,111	N/A	N/A
Cement, Lime	Kilns - Oil	79	1.0	527	N/A	N/A
Cement, Lime	Kilns - Coal	79	1.0	527	N/A	N/A
Coking, Steel	Coke Oven	211	1	N/A	N/A	N/A
Chemical Processes, Wood, Asphalt, Copper, Phosphate	Dryer - Natural Gas	11	1.1	64	N/A	N/A
Chemical Processes, Wood, Asphalt, Copper, Phosphate	Dryer - Oil	16	1.0	168	N/A	N/A
Chemical Processes, Wood, Asphalt, Copper, Phosphate	Dryer - Coal	179	1.0	226	N/A	N/A

[1] Values were originally based on gross calorific value; they were converted to net calorific value by assuming that net calorific values were 5 per cent lower than gross calorific values for coal and oil, and 10 per cent lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net calorific values.

Source: Radian, 1990

TABLE 1-10
RESIDENTIAL SOURCE PERFORMANCE

	Emission Factors (kg/TJ energy input)[1]				
Source	CO	CH_4	NO_x	N_2O	NMVOCs
Wood Pits[2]	4,949	200	147	N/A	N/A
Wood Fireplaces[2]	6,002	N/A	116	N/A	N/A
Wood Stoves[2]	18,533	74	200	N/A	N/A
Propane/Butane Furnaces	10	1.1	47	N/A	N/A
Coal Hot Water Heaters	18	N/A	158	N/A	N/A
Coal Furnaces	484	N/A	232	N/A	N/A
Coal Stoves	3,580	N/A	179	N/A	N/A
Distillate Oil Furnaces	13	5	51	N/A	N/A
Gas Heaters	10	1	47	N/A	N/A

[1] Values were originally based on gross calorific value; they were converted to net calorific value by assuming that net calorific values were 5 per cent lower than gross calorific values for coal and oil, and 10 per cent lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net calorific values.

[2] Emission factors were adjusted to net calorific value assuming a 5 per cent difference in energy content between net calorific value and gross calorific value.

Source. Radian, 1990.

TABLE 1-11
COMMERCIAL SOURCE PERFORMANCE

Source	Emission Factors (kg/TJ energy input)[1]				
	CO	CH_4	NO_x	N_2O	NMVOCs
Wood Boilers[2]	199	15	33	4.3	N/A
Gas Boilers	9.6	1.2	48	2.4	N/A
Residual Oil Boilers	17	1.6	155	46.5	N/A
Distillate Oil Boilers	16	0.6	64	15.7	N/A
MSW Boilers[2]	19	N/A	463	N/A	N/A
Coal Boilers	195	10	236	59.1	N/A
Shale Oil Boilers	17	1.6	186	46.5	N/A
Open Burning - MSW	42 kg/Mg	6.5 kg/Mg	3 kg/Mg	N/A	N/A
Open Burning - Agriculture	58 kg/Mg	9 kg/Mg	N/A	N/A	N/A
Incineration - high efficiency	5 kg/Mg	N/A	1.5 kg/Mg	N/A	N/A
Incineration - low efficiency	10 kg/Mg	N/A	1 kg/Mg	N/A	N/A

[1] Values were originally based on gross calorific value, they were converted to net calorific value by assuming that net calorific values were 5 per cent lower than gross calorific values for coal and oil, and 10 per cent lower for natural gas These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net calorific values

[2] Emission factors were adjusted to net calorific value assuming a 5 per cent difference in energy content between net calorific value and gross calorific value

Source Radian, 1990

TABLE 1-12
UTILITY EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH_4 Reduction (%)	NO_x Reduction (%)	N_2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
Low Excess Air (LEA)	-0.5	+	+	15	N/A	N/A	1970
Overfire Air (OFA) - Coal	0.5	+	+	25	N/A	N/A	1970
OFA - Gas	1.25	+	+	40	N/A	N/A	1970
OFA - Oil	0.5	+	+	30	N/A	N/A	1970
Low NO_x Burner (LNB) - Coal	0.25	+	+	35	N/A	N/A	1980
LNB - Tangent. Fired	0.25	+	+	35	N/A	N/A	1980
LNB - Oil	0.25	+	+	35	N/A	N/A	1980
LNB - Gas	0.25	+	+	50	N/A	N/A	1980
Cyclone Combustion Modification	0.5	N/A	N/A	40	N/A	N/A	1990
Ammonia Injection	0.5	+	+	60	N/A	N/A	1985
Selective Catalytic Reduction (SCR) - Coal	1	8	+	80	N/A	N/A	1985
SCR - Oil, AFBC	1	8	+	80	N/A	N/A	1985
SCR - Gas	1	8	+	80	60	N/A	1985
Water Injection - Gas Turbine Simple Cycle	1	+	+	70	N/A	N/A	1975
SCR - Gas Turbine	1	8	+	80	60	N/A	1985
Retrofit LEA	-0.5	+	+	15	N/A	N/A	1970
Retrofit OFA - Coal	0.5	-	+	25	N/A	N/A	1970
Retrofit OFA - Gas	1.25	-	+	40	N/A	N/A	1970
Retrofit OFA - Oil	0.5	-	+	30	N/A	N/A	1970
Retrofit LNB - Coal	0.25	-	+	35	N/A	N/A	1980
Retrofit LNB - Oil	0.25	+	+	35	N/A	N/A	1980
Retrofit LNB - Gas	0.25	+	+	50	N/A	N/A	1980
Burners Out of Service	0.5	+	+	30	N/A	N/A	1975

[1] Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement

[2] Date technology is assumed to be commercially available

Note A "+" indicates negligible reduction

Source Radian, 1990

TABLE 1-13
INDUSTRIAL BOILER EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH_4 Reduction (%)	NO_x Reduction (%)	N_2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
Low Excess Air (LEA)	-0.5	+	+	15	N/A	N/A	1970
Overfire Air (OFA) - Coal	0.5	+	+	25	N/A	N/A	1970
OFA - Gas	1.25	+	+	40	N/A	N/A	1970
OFA - Oil	0.5	+	+	30	N/A	N/A	1970
Low NO_x Burner (LNB) - Coal	0.25	+	+	35	N/A	N/A	1980
LNB - Oil	0.25	+	+	35	N/A	N/A	1980
LNB - Gas	0.25	+	+	50	N/A	N/A	1980
Flue Gas Recirculation	0.5	+	+	40	N/A	N/A	1975
Ammonia Injection	0.5	+	+	60	N/A	N/A	1985
Selective Catalytic Reduction (SCR) - Coal	1	8	+	80	N/A	N/A	1985
SCR - Oil, AFBC	1	8	+	80	N/A	N/A	1985
SCR - Gas	1	8	+	80	60	N/A	1985
Retrofit LEA	-0.5	+	+	15	N/A	N/A	1970
Retrofit OFA - Coal	0.5	+	+	25	N/A	N/A	1970
Retrofit OFA - Gas	1.25	+	+	40	N/A	N/A	1970
Retrofit OFA - Oil	0.5	+	+	30	N/A	N/A	1970
Retrofit LNB - Coal	0.25	+	+	35	N/A	N/A	1980
Retrofit LNB - Oil	0.25	+	+	35	N/A	N/A	1980
Retrofit LNB - Gas	0.25	+	+	50	N/A	N/A	1980

[1] Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement.

[2] Date technology is assumed to be commercially available.

Note: A "+" indicates negligible reduction.

Source: Radian, 1990

TABLE 1-14
KILN, OVENS, AND DRYERS EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH_4 Reduction (%)	NO_x Reduction (%)	N_2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
LEA - Kilns. Dryers	-6.4	+	+	14	N/A	N/A	1980
LNB - Kilns. Dryers	0	+	+	35	N/A	N/A	1985
SCR - Coke Oven	1.0	8	+	80	60	N/A	1979
Nitrogen Injection	N/A	N/A	N/A	30	N/A	N/A	1990
Fuel Staging	N/A	N/A	N/A	50	N/A	N/A	1995

[1] Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement

[2] Date technology is assumed to be commercially available.

Note: A "+" indicates negligible reduction.

Source: Radian, 1990.

TABLE 1-15
RESIDENTIAL AND COMMERCIAL EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH_4 Reduction (%)	NO_x Reduction (%)	N_2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
Catalytic Woodstove	-44	90	90	-27	N/A	N/A	1985
Non-Catalytic Modified Combustion Stove	-30	15	50	-5	N/A	N/A	1985
Flame Retention Burner Head	-9	28	N/A	N/A	N/A	N/A	
Controlled Mixed Burner Head	-7	43	N/A	44	N/A	N/A	
Integrated Furnace System	-12	13	N/A	69	N/A	N/A	
Blueray Burner/Furnace	-12	74	N/A	84	N/A	N/A	
M.A.N. Burner	-13	N/A	N/A	71	N/A	N/A	1980
Radiant Screens	-7	62	N/A	55	N/A	N/A	
Secondary Air Baffle	N/A	16	N/A	40	N/A	N/A	
Surface Comb. Burner	N/A	55	N/A	79	N/A	N/A	
Amana HTM	-21	-55	N/A	79	N/A	N/A	
Modulating Furnace	-7	N/A	N/A	32	N/A	N/A	
Pulse Combuster	-36	N/A	N/A	47	N/A	N/A	
Catalytic Combuster	-29	N/A	N/A	86	N/A	N/A	
Replace Worn Units	N/A	65	N/A	N/A	N/A	N/A	
Tuning, Seasonal Maintenance	-2	16	N/A	N/A	N/A	N/A	
Reduced Excessive Firing	-19	14	N/A	N/A	N/A	N/A	
Reduced Excessive. Firing with New Retention Burner	-40	14	N/A	N/A	N/A	N/A	
Positive Chimney Dampers	-8	11	N/A	N/A	N/A	N/A	
Increased Thermostat Anticipator	-1	43	N/A	N/A	N/A	N/A	
Night Thermostat Cutback	-15	17	N/A	N/A	N/A	N/A	
Low Excess Air	-0 8	N/A	N/A	15	N/A	N/A	1970
Flue Gas Recirculation	0 6	N/A	N/A	50	N/A	N/A	1975
Over-fire Air	1	N/A	N/A	20-30	N/A	N/A	1970
Low NO_x Burners	0 6	N/A	N/A	40-50	N/A	N/A	1980

[1] Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement.

[2] Date technology is assumed to be commercially available.

Source: Radian, 1990.

TABLE I-16
FUEL PROPERTIES[1]

Fuel	Net Calorific Value (TJ/kilotonne)[2]	Carbon (wt percent)
GAS		
Butane/Propane	45 7	82.0
Coke Oven Gas	36 7	56.1
Methane (pure)	45 0	75.0
Natural Gas	46.0	70.6
Process Gas	48.6	70.6
LIQUID		
Crude Shale Oil	40.9	84 5
Diesel/Distillate	42 9	87.2
Gasoline	116 9 MJ/gal	85 7
Jet Kerosene	41 0	86.1
Methanol	56.1 MJ/gal	37 5
Residual Oil	40 9	85 6
SOLID		
Bagasse/Agriculture	8 6	22.6
Charcoal	27.6	87 0
Coal	22.0	65 0
MSW	10.7	26 7
Wood[3]	18 5-21 3	45.0

[1] Values were originally based on gross calorific value: they were converted to net calorific value by assuming that net calorific values were 5 per cent lower than gross calorific values for coal and oil, and 10 per cent lower for natural gas These percentage adjustments are the OECD IEA assumption on how to convert from gross to net calorific values

[2] Unless otherwise indicated

[3] These values are based on weight as oven dry biomass Heating values are from Ratnasari 1993, Pinguelli, et. al 1993 These are papers distributed at the Sao Jose dos Campos workshop in March 1993

Source Adapted from Radian 1990

1.5.4 Discussion Of Direct GHGs

In the initial stages of the IPCC/OECD programme it was recognised that work on both methods development and national inventories needed to be prioritised, as it was not possible to deal with all of the gases and sources simultaneously. Priority was given to the direct GHGs in the order: carbon dioxide, methane and nitrous oxide (IPCC/OECD, 1991). Carbon dioxide from fuel combustion has been discussed in detail in the previous section It is discussed again here briefly to emphasise the possible linkage of detailed carbon dioxide calculations with the detailed approach required for estimation of other GHGs from combustion.

Methods for estimating emissions of methane and nitrous oxide are not yet well established, but are evolving rapidly based on a great deal of research underway within the global climate change research community and elsewhere. For this reason, expert groups have been established to recommend improvements in estimation methods for a variety of source categories - including fuel combustion - which produce these gases. Information developed by these groups provides some improvements in estimation methods as described below.

Carbon Dioxide (CO_2): The IPCC Reference Approach to estimation of CO_2 emissions from fuel combustion is described in the previous section. This method is designated as a reference method because it is transparent, easy to implement, and produces very reliable and comparable estimates for all IPCC countries. However, it is also clear that more detailed information on CO_2 emissions by source type can be useful to most countries. Countries which have detailed data bases for estimating emissions of non-CO_2 gases are encouraged to also estimate CO_2 emissions at a "bottom-up" level of detail based on the data developed to estimate non-CO_2 emissions.

Specifically, in order to estimate non-CO_2 emissions using the emission factors provided in Tables 1-7 to 1-11, countries will need to determine the amount of energy consumed by sector, technology type, and fuel type Since the fuel type is known, the carbon emission factors provided in Table 1-1 by fuel type could, in theory, be applied to the total amount of input energy for each fuel/technology type by sector to determine total carbon consumed for that category. To determine total CO_2 emissions, one would sum across all technology/fuel combinations and all sectors, and then follow the steps outlined in the CO_2 section including adjusting for any carbon unoxidised during combustion (see Table 1-6) and carbon stored in non-energy products (see Table 1-5).

As noted in the previous section, there may be some variations in the carbon emission factors due to variations in fuel quality, and very likely will be differences in fraction oxidised for different technologies. If more detailed factors are available based on local conditions and measurements, these should be used and documented. In addition, as discussed in the previous section, there are a number of complex accounting problems which can be ignored at the "top-down" level, but have to be addressed at a "bottom-up" level. For example, accounting for carbon released during transformation of energy from one form to another. The IPCC *Guidelines* do not yet provide detailed guidance for dealing with these complexities. Rather, it is recommended that national experts use their own judgement to deal with the detailed questions which must be answered at the "bottom-up" level. All countries must also prepare estimates using the IPCC Reference Approach and are recommended to reconcile the results. This will help identify any carbon in original fuels (e.g., transformation losses) which may not have been accounted for in the detailed "bottom-up" accounts.

Methane (CH_4). CH_4 is produced in small quantities from fuel combustion due to incomplete combustion of hydrocarbons in fuel. In large, efficient combustion facilities, the emission rate is very low. In smaller combustion sources, emissions rates can be higher, particularly where smouldering occurs. In global terms, total emissions from this source category (here defined to exclude "traditional" biomass burning discussed in the next section) are believed to be small relative to other anthropogenic sources. Nevertheless, because of the importance of this gas, these emissions are being studied carefully.

In a background paper prepared for the informal experts group, Berdowski, et al., (1993) summarised the average emission rates for fuel combustion within broad subsectors. The highest rates of methane emissions from fuel combustion are reported for residential applications, where coal and "traditional" biomass fuels are used in small stoves for cooking and heating. Emissions from "traditional" fuels such and fuelwood and agricultural residues are discussed in the next section. Emissions from coal use in residential stoves can also be quite high relative to other combustion applications, as shown in Table 1-17. This table gives average emission factors for broad classes of combustion. It is clear that actual emissions would vary within each category by technology type, fuel quality, and operating conditions. However, the very aggregated information presented is sufficient to show that methane emissions from fossil fuel combustion in large scale utility and industrial applications are low, with utility emission rates being less than 1 per cent of average rates for residential coal combustion.

Based on the average emission factors in Table 1-17, Berdowski, et al., (1993) estimate global emissions from residential coal use to be in the range of 2.5-5.0 Tg/year, although residential coal use is common in only a few countries. The total emissions from utility and industrial coal use and all other fossil fuel use was estimated to be less than 1.5 Tg/year. Despite the fact that large amounts of fuel are used in these latter applications, the very low average emission rates result in very small contributions to total emissions.

TABLE 1-17
GLOBAL EMISSION FACTORS AND EMISSIONS OF METHANE FROM COMBUSTION OF SOLID FUELS

Fuel (type)	Emission factor (kg/TJ)		
	Utilities	Industry	Residential
Coal	1	10	300 (range 200-400)
Residual oil	3	3	-
Distil. oils	-	1	7
Natural gas, LPG	1	4	3

Table adapted from Berdowski, et al., 1993

References: For residential coal use, US EPA, 1985; Zeedijk, 1986. All other categories from Veldt, 1991

Nitrous Oxide (N_2O): N_2O is produced from combustion of fuels, although this source category (stationary combustion, excluding "traditional" biomass burning) is presently considered to be minor, relative to other anthropogenic source categories. The mechanisms that cause the formation of N_2O during the combustion of fossil fuel are now fairly well understood (see De Soete, 1993). The basic knowledge on both gas phase and heterogeneous N_2O chemistry is well able to explain and to forecast, at least in a qualitative manner, N_2O emissions from different combustion sources and flue gas treatment techniques

Nitrous oxide (N_2O) is produced directly from the combustion of fossil fuels. Gas phase N_2O chemistry is relatively well understood as it is part of N-O kinetics and N_2O appears as a by-product of the so-called fuel-N-O mechanism. For combustion temperatures well below 1000 K or above 1200 K the emission factor for N_2O is almost zero or negligible; in the temperature range between about 800 and 1100 K N_2O emissions are reaching the highest levels with a maximum around 1000 K. Increasing the oxygen concentration or the pressure tends to increase the emissions.

Fundamental studies of non-catalytic heterogeneous reactions on the formation and destruction of N_2O only started in recent years, so the available experimental data are still rather scarce. The main mechanisms for the N_2O chemistry appear to be: destruction of N_2O on bound carbon atoms, the formation of N_2O from char bound nitrogen atoms, and the formation of N_2O from NO and reduced sulphates. Catalytic N_2O chemistry may play a role in the following cases:

- at overall reducing conditions (catalysts in spark ignition cars and trucks),
- at overall oxidising conditions (de-NO_x-techniques such as Selective Catalytic Reduction (SCR), emission abatement of diesel engines and lean-burn spark ignition engines), and
- catalytic formation and destruction (e.g. during fluidised bed combustion caused by the presence of calcium oxide).

Recent re-evaluation of available emission factor data from fuel combustion showed that in measurements before July 1988 a so-called artefact often appeared stemming from the presence of NO_x and SO_2 in samples, which resulted in erroneous emission factors which were much too high, thereby highly overestimating the importance of this source category (Muzio and Kramlich, 1988). Since the recognition of this artefact in June 1988, new measurements have led to new reliable emission factors from different conventional stationary combustion sources (De Soete, 1993).

Emission factors can be limited to one value per fuel type for all applications, since relevant knowledge is now readily available (see De Soete (1993) and references therein). Atmospheric (Pressurised) Fluidised Bed Combustion (A(P)FBC) emissions are dependent on the rank of the coal: brown coal produces less emissions than bituminous coal. The emission factors for waste combustion and especially for sludge incineration are very high, with a tendency to increase when FBC technology is applied.

For combustors with application of catalytic emission reduction techniques (e.g. SCR or Non-Catalytic Selective Reduction (NCSR) of NO_x), estimated emission factors are also available. NCSR experiments suggest that the application of this control technology increases the emission factor for N_2O; for SCR no differences are observed. In the case of NCSR the N_2O emissions are higher from urea or cyanuric acid injection than in the case of ammonia injection. These control technologies may not only be applied on large scale facilities exploited by utilities or industry, but also to modern woodstoves. Emission factors for the latter categories are uncertain and a range is more appropriate. Default uncertainty ranges still have to be determined, but a preliminary range is presented in this report.

Default emission factors and uncertainty ranges are shown in Table 1-18. When a country has its own locally determined emission factors, these are of course preferred to the default factors reported here. However, care should be taken that no artefact data were used in deriving the factors.

Reliable emission factors for non-commercial fuel combustion, in particular fuelwood and charcoal, are not yet available because of lack of data on emission measurements for these combustion technologies. This refers amongst others to fuelwood, charcoal (production and use in residential, commercial and industrial sectors), crop residues and dung. Published data are scarce and it is questionable how representative they are for global application. Also, in the preparation of national inventories care should be taken to avoid double counting, since emissions from fuelwood use may also be included in the category of biomass burning (Olivier, 1993).

TABLE 1-18
ESTIMATED DEFAULT EMISSION FACTORS FOR STATIONARY COMBUSTION FACILITIES

Technology	Emission factors (kg N_2O/TJ energy input) (or g N_2O/tonne waste)	Uncertainty range (ibidem)
Conventional facilities, uncontrolled		
Coal	1.4	0-10
Oil	0.6	0-2.8
Gas	0.1	0-1.1
Conventional facilities, controlled		
Selective catalytic reduction (SCR) of NO_x	see uncontrolled	see uncontrolled
NCSR	NA	10-100***
Other combustion facilities:		
Fluidised bed combustion - hard coal **	NA	10-95**
FBC - brown coal, peat, wood **	NA	10-30**
Gas turbines - oil, gas	NA	0-5*

Note NA = Not Available

** If the combustion temperature exceeds 1000 °C one may use a range of 0-10.

*** Preliminary estimate with ammonia injection at lower end and with urea injection at higher end of range

Source De Soete (1993) and references therein

1.5.5 Discussion Of Indirect GHGs

The IPCC/OECD programme has not yet addressed the indirect GHGs in detail. This is consistent with the initial priorities within the IPCC/OECD programme As noted above, fuel combustion is a major source for all of these gases. Because they are important contributors to a range of local and regional, as well as global atmospheric pollution problems, NO_x, CO and NMVOC have been widely studied and reported The Radian data cited above reflect estimates of performance ranges of main combustion technologies in place world-wide, as of 1990 In all cases they are averages over a range of technologies, fuel qualities, and operating conditions. However, since in most instances the data are based on measurement samples taken from the United States, they represent averages of operating conditions, sizes and vintages of units found there, and so may not be applicable to conditions in other countries

More detailed emission factors that are representative of the precise technologies and other conditions in a particular country would always be desirable National experts working on detailed emission of non-CO_2 GHGs (particularly the indirect gases) should consult the extensive literature on emission factors and other estimation procedures which has been developed by other inventory programmes outside of the framework of the IPCC/OECD programme. As distinguished from the Radian emission factors, these data generally contain more technology detail, and are further broken down by size of the various technologies. There is also a slight difference in the technology representation, but this may be more a terminology than a technical difference. The specific nature of these control assumptions should be known and carefully matched with actual conditions in the specific country in selecting the specific factors to be used.

Some key examples of data sources are:

- Default Emission Factor Handbook (European Environment Agency Taskforce, 1992);
- US EPA's Compilation of Air Pollutant Emissions Factors (AP-42), 4th Edition 1985, (US EPA, 1985), and Supplement F, (US EPA, 1993);
- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987)
- Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993)
- Joint Emission Inventory Guidebook (CORINAIR/EMEP, 1995 forthcoming);
- EMEP and CORINAIR Emission Factors and Species Profiles for Organic Compounds. (Veldt, 1991);
- Other National Compilations of Emission Factors Include

- Netherlands	Bakkum, et al., 1987, Okken, 1989
- Norway	Statens forurensningstilsyn, 1990
- Germany	Brieda, 1989, Fritsche, 1989, Rentz et al., 1988, Walbeck, et al., 1988
- Japan	JAERI, 1988
- United Kingdom	Eggleston and McInnes, 1987

Nitrogen Oxides (NO_x): Electricity generation and industrial fuel combustion activities are similar in that they provide combustion conditions conducive to NO_x formation. NO_x emissions depend in part on the nitrogen contained in the fuel (this may be especially important for coal), but more importantly on the firing configuration of the technology. Excess air and high temperatures contribute to high NO_x emissions. Such conditions are highly variable by type of boiler; for instance, for oil-fired plants, tangential burner configurations generally have lower emission factors than horizontally opposed units. Also, the size of the boiler will affect the NO_x emission rate due to the lower temperatures of smaller units.

Usage of the technology can also significantly alter the pattern of NO_x emissions. Measurements of emissions show a 0.5 to 1.0 per cent decrease in NO_x emission rates for every 1.0 per cent decrease in load from full load operation. That is, as the usage rate increases, so does the emission rate associated with the facility.

Finally, control policies and related technological changes to meet emission limits directly influence NO_x emissions. Emissions from large facilities can be reduced by up to 60 per cent by straightforward adjustments to the burner technology.[17] These adjustments are often standard in new facilities, but may not exist in older facilities in many OECD countries and may be especially rare in non-OECD countries. NO_x controls may also increase the rate of CO emissions. Information on the stock of combustion facilities, their vintage, and level of control are therefore necessary to accurately evaluate emissions from large combustion facilities.

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[17] This can be done, for example, by limiting the excess air in combustion or by staging the combustion process.

NO_x emissions from small combustion facilities (small industry, commercial and residential) tend to be much less significant than for large facilities due to lower combustion temperatures. Nevertheless, emissions will depend on the specific combustion conditions of the activity in question, and an effort should be made to carefully characterise the type of activity, on average, in order to select appropriate emission factors.

For many years, NO_x has been the target of environmental policies for its role in forming ozone (O_3), as well as for its direct acidification effects. As a result, NO_x emission inventories and related data such as emission factors are more widely available than those for the other non-CO_2 greenhouse gases considered here. The sources listed above provide a large number of emission factors depending on technology, fuel characteristics, operating conditions, size, vintage, etc.

Carbon Monoxide (CO): By comparison to NO_x, combustion conditions in large facilities are less conducive to formation and release of CO emissions. CO is a gaseous combustible that is emitted in small quantities due to incomplete combustion. It also has been the target of emission control policies in some countries and hence must be estimated with these controls in mind. It is directly influenced by usage patterns, technology type and size, vintage, maintenance and operation of the technology. Emissions can vary by several orders of magnitude, for example, for facilities that are improperly maintained or poorly operated, such as may be the case for many older units. Similarly, during periods of start-up, combustion efficiency is lowest, and CO emissions are higher than during periods of full operation.

Size of the unit may indicate that combustion is less controlled and hence the CO emission factors for smaller units are likely to be higher than for large plants. Also wood stoves, due to their largely inefficient combustion of the fuel, have particularly high emission rates of CO. For these reasons, an understanding of commercial and residential activities are key to the estimation of CO from stationary sources, particularly in non-OECD countries where residential consumption of wood and other vegetal fuels is commonly high.

CO emissions from stationary sources are estimated in the same way as for NO_x emissions. Detailed energy data by end-use provide the basis for estimation, but there may be significant variation in the precise size and type of combustion technologies in place. A main combustion source of CO is the residential sector, where there is great variation in technology by geographic region due to a variety of manufacturers as well as unconventional combustion modes that may be found throughout the world. This may be especially the case for wood fuel use[18] – an area where data are weak both on total energy consumption and characterisation of the range of technologies in use in different regions of the world.

With these notes of caution in mind, another data source for CO emission factors from stationary sources is provided in *L'Office Fédéral de la Protection de L'Environnement*, Bern, Switzerland (OFPE, 1987). This source is based on other European sources; it does provide a range for each of the activity categories for CO emission factors when combined with the Radian factors above

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[18] Some wood fuel use which is covered in commercial energy statistics and for which technology and emission factor data are known, may be included in the calculation described in this section. For developing countries, however, there is frequently a large share of "traditional" biomass use, which is generally not included in commercial energy statistics, and data on the mix of specific technologies used is lacking. For these countries an optional simpler method of calculating emissions from "traditional" biomass fuel use is provided in the next section. National experts must take care to ensure that there is not double counting, if more than one method is used.

Non-Methane Volatile Organic Compounds (NMVOC): As with CO, combustion conditions in large facilities are less conducive to formation and release of NMVOCs. NMVOCs are, like CO, gaseous combustibles that are emitted in small quantities due to incomplete combustion. They have also been the target of emission control policies in some countries and hence must be estimated with these controls in mind. They are directly influenced by usage patterns, technology type and size, vintage, maintenance and operation of the technology. Emissions can vary by several orders of magnitude, being particularly high, for example, for facilities that are improperly maintained or poorly operated, such as may be the case for many older units. Similarly, during periods of start-up combustion efficiency is lower, and NMVOC emissions are higher than during periods of full operation.

Size of the unit may indicate that combustion is less controlled and hence the NMVOC emission factors for smaller units are likely to be higher than for large plants. Also wood stoves, due to their largely inefficient combustion of the fuel, have particularly high emission rates of NMVOCs. For these reasons, an understanding of commercial and residential activities is vital to the estimation of these greenhouse gases, particularly in non-OECD countries where residential consumption of wood and other vegetal fuels is commonly high.

Extensive emission factor data for NMVOCs from fuel combustion sources are available from most of the sources listed above. In some older sources total volatile organic compounds, i.e., including methane, have been considered together. The recent work of the CORINAIR programme, the US EPA sources cited above, and most other more current sources distinguish NMVOC from methane in emission factors and emission estimates. Analysts should be careful to understand the exact category of pollutant being specified when selecting emission factors. There is considerable uncertainty in most available information on NMVOC emissions, as is the case for methane.

The CORINAIR and US EPA factors show rough agreement on most categories of fuel combustion, though both acknowledge considerable uncertainty. These data highlight the importance of small combustion facilities as the main energy-related source of emissions, but emission factor data for small facilities is also particularly unreliable. In any case, a review of the literature confirms that NMVOCs from fuel combustion (excluding traditional biomass fuels) is a relatively minor source of total NMVOC emissions.

1.5.6 Priorities For Future Work

Data for Non-OECD Regions of the World

A high priority for follow-up work is to develop representative energy technology and emission factor data for developing countries and other non-OECD regions of the world. Emission factor data are likely to differ significantly among OECD and non-OECD regions due to differences in types of fuels, combustion technologies, vintage, size and operating conditions.

Uncertainty in Emission Factor Data

Emission factor data are normally presented as single point estimates. In fact, emission factors are characterised by a great deal of variation around these point estimates. Therefore, it would be preferable to have emission factor data presented with appropriate ranges, as well as with accompanying statistics such as representative operating conditions.

These statistics should help relate the range of emission factors to the associated operating conditions.

Priorities by Gas

Emission factor data are particularly weak for N_2O, CH_4, NMVOC and CO. Monitoring and measurement studies for these gases to improve the base emission factor data would further the development of complete greenhouse gas inventories. The extent to which it is necessary to fill data gaps depends upon the importance of these greenhouse gases in national inventories.

However, CH_4 and N_2O emissions from stationary combustion sources (excluding "traditional" biomass fuel burning) are a small share of total emissions, although a few specific technologies appear to have higher emission rates and may warrant extensive study: see Tables 1-7 to 1-11.

Similarly, NMVOC and CO can be quite significant in areas where wood or vegetal fuels make up a major share of total energy consumption. Again, these are areas with substantial "traditional" biomass fuel consumption, discussed in the next section.

Development of Simplified Workbook Methods

As noted several times in this chapter, the non-CO_2 gases do not lend themselves to simple "top-down" aggregate emissions estimation. Nonetheless, the IPCC and parties to the Framework Convention on Climate Change are committed to providing methods which are both comprehensive over all GHGs and accessible to all participating countries. Further work is needed to define default methods for estimating the non-CO_2 gases from fuel combustion. This may require development of a "mid-level" approach which incorporates more detail than the national top down CO_2 approach, but provides an intermediate level of detail which can capture the most important variations by technology without going directly to the most detailed level of technology information which may be difficult for some countries to obtain.

Reconciling Energy and ISIC Categories with Engineering-Technology Category Definitions

A priority for countries constructing GHG emission inventories on a "bottom-up" basis is to ensure that the basic, detailed activity data covering the fuel consumption by type of combustion plant should be linked to the economic activity sector classification (ISIC or NACE). This will permit a far larger range of abatement policy analyses to be undertaken than at present.

1.6 Greenhouse Gas Emissions from Mobile Sources

1.6.1 Overview

This section discusses emissions of greenhouse gases from mobile sources, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4), nitrous oxide (N_2O), and non-methane volatile organic compounds (NMVOCs). Emissions from mobile sources are most easily estimated by major transport activity, i.e., road, air, rail, and ships. Several major fuel types need to be considered, including gasoline, diesel, jet kerosene, aviation gasoline, natural gas, liquefied petroleum gas, and residual fuel oil. Road transport accounts for the majority of mobile-source fuel consumption (e.g., 82 per cent in 1988 for the OECD), followed by air transport (about 13 per cent). This suggests that the primary emphasis in developing emission inventories should be placed on road vehicles, followed by aircraft.

As one of the major energy-consuming sectors, transport is a significant source of CO_2 emissions. As discussed previously, these emissions should be accounted for in the "top-down" IPCC Reference Approach to CO_2 from fuel combustion. However, it is also useful to develop more detailed information about the role of specific end-use activities, such as mobile sources, in causing CO_2 emissions. National experts are therefore encouraged to also calculate CO_2 emissions at a more detailed level (as described in this section for transport) and to aggregate these estimates up for comparison with the Reference Approach. Therefore, the discussion in this section includes information needed to estimate CO_2 emissions as well as other gases at a detailed level.

Motor vehicles release a large portion of total anthropogenic NO_x emissions. These emissions are related to air-fuel mixes and combustion temperatures, as well as pollution control equipment. For uncontrolled vehicles, NO_x emissions from diesel-fueled vehicles are generally lower than from gasoline-fueled vehicles, and lower from heavy duty vehicles (HDV) than light duty vehicles (LDV) on an emissions per tonne-kilometre basis. HDV still contribute significant emissions which are more difficult to control than light duty vehicles.

The majority of CO emissions from fuel combustion come from motor vehicles. CO emissions are a function of the efficiency of combustion and post-combustion emission controls. Emissions are highest when air-fuel mixtures are "rich," with less oxygen than required for complete combustion. This occurs especially in idle, low speed, and cold start conditions in spark ignition engines.

CH_4 and NMVOC emissions are a function of the methane content of the motor fuel, the amount of hydrocarbons passing unburnt through the engine, and any post-combustion control of hydrocarbon emissions, such as use of catalytic converters. In uncontrolled engines, emissions of unburned hydrocarbons, including CH_4, are generally highest at low speeds and when the engine is idle. Poorly-tuned engines (typical of many developing countries) may have particularly high output of total hydrocarbons, including CH_4. Emissions are also dependent on engine type, emission controls and the fuel combusted.

N_2O emissions from vehicles have only recently been studied in detail. Emissions from this source are still thought to be small relative to total anthropogenic emissions. Emission rates are, however, substantially higher when some emission control technology (especially catalysts on road vehicles) are used, and this could cause the total emissions to grow in the future.

Emission control policies adopted in many OECD member countries will substantially reduce CO, NMVOC, CH_4, and NO_x emissions per automobile, but may cause N_2O emissions to increase.

Organisation of this section

The next subsection provides a discussion of the basic inventory methodology recommended for mobile source emissions. In the following subsection, illustrative information on emission factors is provided. This is summarised from a 1991 document, but is useful in illustrating the range of mobile source types and rates of emissions of various gases. Subsequently, some more recent information, developed by expert advisory groups to the IPCC/OECD programme, is provided on two direct GHGs - N_2O and CH_4. A short subsection discusses indirect GHGs - NO_x, CO and NMVOC. No new work has been done within the IPCC/OECD programme on these gases, but considerable detailed information is available from other national and international emissions inventory programmes. Some key references to this body of technical work are provided. A final subsection suggests some priorities for future work on GHG emissions from mobile sources.

1.6.2 Basic Inventory Method: Mobile Source Emissions

Estimation of mobile source emissions is a very complex undertaking that requires consideration of many parameters, including:

- transport class
- fuel consumed
- operating characteristics
- emission controls
- maintenance procedures
- fleet age

The need for data on several parameters and the wide variety of conditions that can affect the performance of each category of mobile sources makes it very difficult to generalise the emission characteristics in this area. This area is so complex that is difficult even for countries with extensive experience to develop highly precise emission inventories.

Nevertheless, a basic emission estimation methodology was developed and included in the report of the OECD Experts Meeting which was circulated to IPCC national experts as a starting point for the methods development programme (OECD, 1991). This basic discussion is still useful and repeated with few changes in this section. The method is consistent with the calculations carried out in those countries which already have detailed mobile source emissions inventory data bases. It is presented in a simplified, aggregate form to assist countries with limited experience in estimating emissions from mobile sources.

To estimate greenhouse gas emissions from mobile sources, basic information is required on the types of fuels consumed in the transport sector, the combustion technologies that are used to consume the fuels, operating conditions during combustion, and the extent of emission control technologies employed during and after combustion. The basic calculation for estimating these emissions can be expressed as:

$$\text{Emissions} = \sum (EF_{abc} \times \text{Activity}_{abc})$$

where: EF = emission factor

Activity = amount of energy consumed or distance travelled for a given mobile source activity

a = fuel type (diesel, gasoline, LPG, bunker, etc.)

b = vehicle type (e.g., passenger, light-duty or heavy-duty for road vehicles)

c = emission control

Based on this formula, the following basic steps are required to estimate mobile source emissions:

- Determine the amount of energy consumed by fuel type for the major transport modes using national data or, as an alternative, IEA or UN international data sources (all values should be reported in terajoules).
- For each fuel type, determine the amount of energy that is consumed by each vehicle type, e.g., light-duty gasoline vehicles, etc. (all units are in terajoules). If distance travelled is the activity measure, determine the total distance travelled by each vehicle type. In this case, the energy consumption associated with these distance travelled figures should be calculated and aggregated by fuel for comparison with national energy balance figures. If necessary, further subdivide each vehicle type into uncontrolled and key classes of emission control technology.
- Multiply the amount of energy consumed, or the distance travelled by each category of vehicle or vehicle/control technology, by the appropriate emission factor for that category. Data presented in the next section (Illustrative Emission Factors) can be used as a starting point. However, national experts are encouraged to consult other data sources referenced in this chapter or locally available data before determining appropriate factors for a particular country.
- Emissions can be summed across all categories of fuel and technology type, including for all levels of emission control, to determine total emissions from mobile source-related activities

Regardless of the specific methodology that is used to determine emissions, it is important to remember that there is a substantial amount of uncertainty surrounding the estimates. National experts are encouraged to provide indications of uncertainty in their estimates as described in *Volume 1: Reporting Instructions*.

Data Sources

Emission factors (such as those in Tables 1-19 through 1-31) can be used only if energy consumption can be disaggregated by the fuel and vehicle/control technology categories. For example, for transportation needs, information is required on the percentage of light-duty versus heavy-duty vehicles by fuel type (gasoline- versus diesel-fueled) and the extent of emission controls for each category. There is no single data source that comprehensively provides all relevant information. There are several sources, however, that can help to determine this information.

For example, activity data for vehicle fleets will be needed. There are two main international sources of data available on transport, both of which are recommended as the international point of reference. For road transport, both the *Annual Bulletin of*

Transport Statistics for Europe (UNECE, 1989) and the *World Road Statistics* (International Road Federation, 1990) provide annual data on vehicle fleet movements and traffic conditions. While the former is more detailed for the various modes of transport the data relate to Europe only. The latter is world-wide in coverage but provides only a few key statistics. These include data on vehicles in use, road traffic, motor fuels, and data on the flows of vehicles produced and sold (imports and exports) among countries. Individual regional and national data sources can also be used and may in fact be more disaggregated and up-to-date than these international data sources.

Information on energy consumption in the transport sector is also needed to determine emissions. As discussed earlier, the most reliable sources for international energy statistics are the International Energy Agency and the UN Statistical Division, where data on transport activities are detailed by fuel type and basic transport mode. These energy consumption data are available for most of the world's mobile emission sources. National energy data sources may be preferable to these international sources but the reporting definitions and conventions of the IEA should be used to summarise these energy data. This provides a check for internal consistency of the energy assumptions used to estimate emissions from mobile-source combustion.

1.6.3 Illustrative Emission Factors

This section summarises results of a detailed analysis of mobile-source emission factors for gases. The tables given cover North American and European vehicles and conditions. A more detailed discussion of the methods and assumptions used for the North American tables can be found in OECD 1991. It has not been possible, in the preparation of this *Reference Manual*, to update this earlier analysis in a systematic way. The results are still useful in illustrating the range of emission rates from different types of vehicles and how those rates vary by vintage and control technology. It is also very useful in providing side-by-side expressions of the same emission factors in three different forms. Therefore, the results are repeated in this section, for illustrative purposes.

The European data are more recent and drawn from the CORINAIR COPERT model However, for actual calculations of national emissions, users are encouraged to also consult a range of more recent and more detailed information sources. Particularly for indirect GHGs, more comprehensive and up-to-date sources are available based on programmes outside the GHG emissions area. More recent data on some gases, and references to other detailed data sources are provided in the gas-by-gas subsections later in this section.

Emission factor estimates are presented for CO_2, CO, NO_x, N_2O, CH_4, and NMVOCs for several classes of highway vehicles, railway locomotives, ships and boats, farm and construction equipment, and aircraft. All emission factor data are stated on the basis of full molecular weight of the respective pollutant; NO_x factors are stated as NO_2

1.6.3.1 Road Vehicles - Conventional Fuels

United States Emission Estimates

Technical Approach

The US emissions estimates for NO_X, CO and NMVOC from highway vehicles were developed directly from the US EPA's MOBILE4 model (EPA, 1989). The model calculates exhaust emission factors for gasoline and diesel fueled US vehicles, based on the year in which they were manufactured. For gasoline vehicles, it also calculates VOC emissions due to evaporative, running and refueling losses (VOC emissions from diesel vehicles due to these causes are negligible).

CH_4 emission factors are derived from model results by subtracting NMVOC from total VOC. The current understanding of CH_4 emissions is very uncertain and the values provided and variations shown across classes of vehicles and technologies imply more precision than is really supported by available measurement data. A summary paper prepared for an experts meeting in 1993 (Berdowski, et al., 1993) suggested values which are somewhat higher for some categories, based on a review of available measurement data. Where applicable, these alternative values are provided in footnotes to tables of illustrative emission factors for comparison.

Assumptions

Specific US model years were used to represent the different possible control technologies. Emissions were calculated for a five year-old vehicle of each type (approximately halfway through their useful lives). Similarly, emissions estimates for advanced-technology vehicles were based on 1990 model vehicles, calculated in 1995. Table 1-19 shows the correspondence between technology types and US model years used to represent them in the model. The conditions chosen for the modelling were "typical" values of 75°F, with a diurnal range from 60 to 85°F (16-30°C), and Reid vapour pressure of gasoline at 9.0 PSI (62 kPa). Average speed was taken as the MOBILE4 default of 31.4 km/hr, typical of uncongested urban driving. An effective inspection / maintenance and anti-tampering program was assumed to be in place.

Since MOBILE4 does not estimate N_2O or CO_2 emissions, these were estimated separately. CO_2 emissions were calculated from typical fuel economy data for US vehicles for representative model years in which the technology was used together with the average carbon content for each type of fuel.[19] Fuel economy estimates for heavy-duty gasoline and diesel trucks are from Machiele (1988), and are from Weaver and Turner (1991) for other vehicle classes. The specific fuel economy value assumed for US vehicles in each case is shown in the tables. The estimated vehicle fuel economies were also used to calculate fuel-specific (g/kg fuel) and energy-specific (g/MJ) emission factors for all of the pollutants. The CO_2 factors on an energy input (g/MJ) were taken from Grubb (1989); all other emission factors are from Turner and Weaver (1991). Since emissions and fuel consumption tend to vary in parallel (vehicles and operating modes causing high emission rates also tend to result in high fuel consumption, and vice versa), these energy-specific emission factors are expected to be more generally applicable than the factors in grams/km.

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[19] As is the convention throughout these *Guidelines*, CO_2 emissions are calculated to include the carbon emitted as CO and as VOC. The rationale for this approach is explained in the Introduction.

Box 2
LIMITATIONS OF MOBILE4 RESULTS

Emission factors for many greenhouse gases from road vehicles have been developed using the MOBILE4 Model as presented in Tables 1-20 to 1-26. This model is one of a series of emissions models developed and periodically updated by the US Environmental Protection Agency for use in its analysis of motor vehicle regulatory and policy issues. The model has been used to derive average emission factors for NO_X, CO, and NMVOC by class of vehicle and for gasoline and diesel fuel. Calculations for other gases and for alternative fuels were done separately.

All "global" average emission factors like these should be considered illustrative and should not be directly used in national emissions calculations. Such values are by necessity based on "global" average assumptions in several key areas. Average emission factors by class of vehicle are sensitive to very specific assumptions including those about

- vehicle models, average age and accumulated mileage
- per cent driving in cold start, hot start and stabilised conditions
- average driving speed
- ambient temperature
- fuel comparison
- rates of tampering with control systems
- proper maintenance

Obviously, many of these assumed conditions will vary significantly from country to country and even by region within countries. For example, the light-duty gasoline vehicle class does not include two-stroke engines, which are not used in the United States, but are important in Central and Eastern Europe. Therefore, "global" illustrative factors should not be used to calculate actual emissions in a specific country.

In addition, the MOBILE4 Model specifically is now out of date. Since this analysis was done (in 1991) several improvements have been based on new information and vehicle testing results. The current version is MOBILE5A[1], which produces somewhat different results. It was not possible to redo the analysis using MOBILE5A for this manual, so the older results are presented to illustrate the range of emission rates from different combinations of vehicle type, control technology and fuel. It should be recognised that emission factors developed using the latest version of the MOBILE Model would be higher for most pollutants. Based on a comparison of the two versions of the Model (as adapted for Canada[2]) the emissions factors for Light-Duty Gas Vehicles increased from MOBILE4 to MOBILE5 by more than 28 per cent for NO_X, 59 per cent for CO and 47 per cent for NMVOC on a grams per mile basis. For other classes of vehicles the values increase by 0-24 per cent for NO_X, 0 5-49 per cent for CO and 3-54 per cent for NMVOC.

For both of the reasons above, **illustrative emission factors** should not be directly used for national calculations. National inventory experts should consult the more detailed references on mobile source emission factors and use these sources to develop or adapt emission factors which are appropriate for their specific conditions. The expert group on GHG emissions from fuel combustion has identified the need for more detailed guidance and assistance to national experts on the development of locally applicable emission factors as a priority for future work.

[1] The MOBILE5A Model and its User Guide can be obtained from the US National Technical Information Service, US Department of Commerce, Springfield, Virginia 22161, United States.

[2] This comparison was reported in comments submitted to the IPCC/OECD Programme by Art Jaques, Environment Canada, May 1994.

N_2O emission factors were developed based on the limited available test data. Prigent and Soete (1989), Dasch (1990 and 1992), Ford (1989-1991), and Warner-Selph and Smith (1991) gave N_2O emissions for light-duty gasoline vehicles which were divided into four groups of technologies: uncontrolled, oxidation catalyst, early three-way catalyst, and modern three-way catalyst technologies. For light-duty gasoline trucks and motorcycles, fuel-specific N_2O emissions were assumed to be the same as for the corresponding passenger car technology. No data on N_2O emissions from heavy-duty gasoline trucks were available, but they were assumed to emit at the same rate per unit of fuel burned as passenger cars having similar technology. However, since these trucks undergo a heavier duty cycle, and experience fewer cold-starts, it was considered more appropriate to use N_2O emission factors based on the US highway fuel economy test (HFET) rather than the cold-start FTP procedure. Fuel-specific N_2O emissions for passenger cars in the HFET procedure were obtained from the same data sources listed above. Dietzmann, Parness, and Bradow (1980) reported N_2O emission factors for heavy-duty diesel vehicles. No N_2O emissions data were available for light-duty diesel vehicles, but they were assumed to have the same fuel-specific emission rates as for diesel passenger cars.

More recent measurements (Dasch, 1992, De Soete, 1993, Ballantyne, et al., 1994) have shown higher values for gasoline fueled passenger cars (see Box 3), although there are still considerable ranges of uncertainty around all estimates. Based on these results, and comments of experts reviewing the draft Guidelines, the more recent values have been substituted in Table 1-20 for cars equipped with oxidation catalysts and advanced three-way catalysts. Given that illustrative emission factors for other gasoline fueled road vehicles were originally derived from the values for passenger cars, the corresponding values for light duty trucks (Table 1-21) and heavy duty vehicles (Table 1-22) were adjusted proportionally to the changes for passenger cars.

Another key issue, which is not reflected in the categories used in the tables, is that **aged catalysts (e.g., after use for 15,000 km) emit N_2O at much higher rates - roughly five times the rates of new catalyst equipped cars.** This is indicated in notes in Tables 1-20 to 1-22 and should be a key consideration in national inventory calculations.

Box 3

RECENT INFORMATION ON N_2O MEASUREMENTS

Since the initial illustrative emission factors were estimated in 1991, a number of measurement studies have been carried out to improve understanding of vehicle N_2O emissions. A recent paper by Ballantyne, et al., (1994) summarised measurements in Canada, the US and Europe.

	Canadian Measurements (Ballantyne, et al., 1994)		US Measurements (Dasch, 1992)		European Measurements (De Soete, 1989)		Values Used in Canadian National Inventory	
	mg/mi	g/km	mg/mi	g/km	mg/mi	g/km	mg/mi	g/km
New three-way catalysts	21-126	0.013-0.078	13-101	0.008-0.06	60-170	0.037-0.106	60	0.04
Aged three-way	72-211	0.045-0.131	-	-	260-356	0.162-0.221	280	0.17
Oxidation catalyst	-	-	3-66	0.002-0.04	120	0.075	120	0.075
No catalyst	-	-	2.4-4.8	0.001-0.003	8-32	0.005-0.02	32	0.02

Results of this analysis are presented by categories defined by the US EPA as listed below:

Table 1-20: Light-duty gasoline passenger cars - vehicles with rated gross weight less than 8,500 lb (3,855 kg) designed primarily to carry 12 or fewer passengers. Five levels of gasoline-vehicle control technology are shown:

1 "Advanced" three-way catalyst values based on current United States technology vehicles, using electronic fuel injection under computer control.

2 "Early" three-way catalyst results representative of vehicles sold in the United States in the early to mid 1980s, which were mostly equipped with carburettors having electronic "trim".

3 Oxidation catalyst systems normally including many of the same techniques, plus a two-way catalytic converter to oxidise hydrocarbons and CO.

4 Non-catalyst emission controls - including modifications to ignition timing and air-fuel ratio to reduce emissions, exhaust gas recirculation (EGR), and air injection into the exhaust manifold.

5 Uncontrolled (still typical of most vehicles around the world)

Table 1-21: Light-duty gasoline trucks - vehicles having rated gross vehicle weight less than 8,500 lb (3,855 kg), and which are designed primarily for transportation of cargo or more than 11 passengers at a time, or which are equipped with special features for off-road operation. They include most pickup trucks, passenger and cargo vans, four-wheel drive vehicles, and derivatives of these. The technology classifications used are the same as those for gasoline passenger vehicles.

Table 1-22: Heavy-duty gasoline vehicles - manufacturer's gross vehicle weight rating exceeding 8,500 lb (3,855 kg). This includes large pickups, vans and special sed trucks using pickup and van chassis, as well as the larger "true" heavy-duty trucks, which have gross vehicle weights of eight short tons or more. In the United States, the large pickups and vans in this category greatly outnumber the heavier trucks, so that the emission factors calculated by MOBILE4, and fuel economy estimates, are more representative of these vehicles. Three levels of emission control technology are shown:

1 Three-way catalyst technology presently used in the United States includes electronically-controlled fuel injection, EGR, air injection, and electronic control of ignition timing, as well as the catalyst itself.

2 Non-catalyst emission controls, including control of ignition timing and air-fuel ratio to minimise emissions, EGR, and air injection into the exhaust manifold to reduce hydrocarbons and CO emissions.

3 Uncontrolled.

Table 1-23: Light-duty diesel passenger cars - a diesel passenger car designed primarily to carry fewer than 12 passengers, with gross vehicle weight less than 8,500 lb (3,855 kg) Three levels of emission control technology are shown:

1 Advanced emissions control utilising modern electronic control of the fuel injection system, and exhaust gas recirculation.

2 Moderate emissions control (achieved by changes in injection timing and combustion system design)

3 Uncontrolled

***Table 1-24:* Light-duty diesel trucks** - light-duty diesel trucks defined like their gasoline counterparts, including weight, utility, and off-road operation features. The technology classifications are the same as those for diesel passenger cars.

***Table 1-25:* Heavy-duty diesel vehicles** - the classification for heavy-duty diesel vehicles is the same as for gasoline vehicles, but the characteristics of US vehicle fleets are different. Heavy-duty diesel vehicles are primarily large trucks, with gross vehicle weight ratings of 10 to 40 tons. Therefore, the MOBILE4 emission factors are more representative of large trucks (and buses) than the smaller pickup and van-type vehicles, and this is reflected in the fuel economy estimates. Three levels of control are presented:

1. Advanced control (for engines meeting US 1991 emissions standards).
2. Moderate control (typical of 1983 US engines).
3. Uncontrolled.

***Table 1-26:* Motorcycles** - The MOBILE4 emission factors for these vehicles are based on the US motorcycle population, which probably reflects higher average power ratings and fuel consumption than for many developing countries. The factors for uncontrolled motorcycles include a mixture of two-stroke and four-stroke engines, with the VOC emissions due primarily to the two-strokes, and the NO_x to the four-stroke engines. The factors for motorcycles with non-catalyst emission controls reflect four-stroke engines only, as US emission control regulations have essentially eliminated two-stroke engines from the market.

TABLE 1-19
EMISSION CONTROL TECHNOLOGY TYPES AND US VEHICLE MODEL YEARS USED TO REPRESENT THEM

Technology	Model Year
Gasoline Passenger Cars and Light Trucks	
Uncontrolled	1963
Non-catalyst controls	1972
Oxidation catalyst	1978
Early three-way catalyst	1983
Advanced three-way catalyst	1990
Heavy-Duty Gasoline Vehicles	
Uncontrolled	1968
Non-catalyst control	1983
Three-way catalyst	1991
Diesel Passenger Cars and Light Trucks	
Uncontrolled	1978
Moderate control	1983
Advanced control	1990
Heavy Duty Diesel Vehicles	
Uncontrolled	1968
Moderate control	1983
Advanced control	1991
Motorcycles	
Uncontrolled	1972
Non-catalyst controls	1990

TABLE 1-20
ESTIMATED EMISSION FACTORS FOR US GASOLINE PASSENGER CARS

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Advanced Three-Way Catalyst Control;[1] Assumed Fuel Economy: 11.9 km/litre						
Total - g/km	0.50	0.020	0.66	3.14	0.019	200
Exhaust	0.50	0.020	0.26	3.14	0.019	200
Evaporative			0.11			
Refuelling			0.15			
Running loss			0.14			
g/kg fuel	7.94	0.32	10.48	49.87	0.30	3172
g/MJ	0.18	0.0072	0.24	1.13	0.0069	69.3
Early Three-Way Catalyst;[1] Assumed Fuel Economy: 9.4 km/litre						
Total - g/km	0.52	0.04	0.67	3.12	0.046	254
Exhaust	0.52	0.04	0.25	3.12	0.046	254
Evaporative		0	0.12			
Refuelling		0	0.16			
Running loss		0	0.14			
g/kg fuel	6.49	0.50	8.36	38.93	0.57	3172
g/MJ	0.15	0.0113	0.19	0.88	0.0130	69.3
Oxidation Catalyst; Assumed Fuel Economy: 6.0 km/litre						
Total - g/km	1.59	0.09	1.75	12.98	0.027	399
Exhaust	1.59	0.09	1.13	12.98	0.027	399
Evaporative		0	0.19			
Refuelling		0	0.21			
Running loss		0	0.22			
g/kg fuel	12.63	0.71	13.90	103.07	0.21	3172
g/MJ	0.29	0.0162	0.32	2.34	0.0049	69.3
Non-Catalyst Control; Assumed Fuel Economy: 6.0 km/litre						
Total - g/km	1.97	0. 74	3.15	23.8	0.005	399
Exhaust	1.97	0. 74	2.14	23.8	0.005	399
Evaporative		0	0.45			
Refuelling		0	0.29			
Running loss		0	0.27			
g/kg fuel	15.64	1.38	25.01	188.99	0.04	3172
g/MJ	0.36	0.0314	0.57	4.30	0.0009	69.3
Uncontrolled; Assumed Fuel Economy: 6.0 km/litre						
Total - g/km	2.14	0.174	6.33	40.62	0.005	399
Exhaust	2.14	0.174	4.36	40.62	0.005	399
Evaporative		0	1.37			
Refuelling		0	0.28			
Running loss		0	0.32			
g/kg fuel	16.99	1.38	50.27	322.56	0.04	3172
g/MJ[2]	0.39	0.0314	1.14	7.33	0.0009	69.3

[1] Recent measurement results (De Soete, 1993, Ballantyne, et al., 1994) have shown that N_2O emissions from aged catalysts, e.g., tested after driving 15,000 - 25,000 km, are substantially higher than from new catalyst-equipped cars. Tests on comparable models show aged catalysts emitting from roughly 30% more to almost 5 times the rate of new equipment. As indicated in Box 3, Environment Canada has used a value almost 5 times as high for aged catalysts in its national inventory calculations.

[2] Berdowski, et al., (1993a) suggest a CH_4 emission factor of 0.057 g/MJ for this vehicle technology class.

TABLE 1-21
ESTIMATED EMISSION FACTORS FOR US LIGHT-DUTY GASOLINE TRUCKS.

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Advanced Three-Way Catalyst Control;[1] Assumed Fuel Economy: 9.4 km/litre						
Total - g/km	0.67	0.04	0.75	4.68	0.024	254
Exhaust	0.67	0.04	0.4	4.68	0.024	254
Evaporative		0	0.1			
Refuelling			0.2			
Running loss			0.04			
g/kg fuel	8.36	0.50	9.36	58.40	0.30	3172
g/MJ	0.19	0.0113	0.21	1.33	0.0068	69.3
Early Three-Way Catalyst[1]; Assumed Fuel Economy: 6.8 km/litre						
Total - g/km	1.00	0.07	1.17	9.23	0.063	350
Exhaust	1.00	0.07	0.78	9.23	0.063	350
Evaporative		0	0.13			
Refuelling		0	0.21			
Running loss		0	0.04			
g/kg fuel	9.08	0.64	10.62	83.76	0.57	3172
g/MJ	0.21	0.0144	0.24	1.90	0.0130	69.3
Oxidation Catalyst; Assumed Fuel Economy: 5.1 km/litre						
Total - g/km	1.62	0.09	1.95	12.15	0.031	466
Exhaust	1.62	0.09	1.22	12.15	0.031	466
Evaporative		0	0.22			
Refuelling		0	0.29			
Running loss		0	0.22			
g/kg fuel	11.03	0.61	13.27	82.70	0.21	3172
g/MJ	0.25	0.0139	0.30	1.88	0.0048	69.3
Non-Catalyst; Assumed Fuel Economy: 5.1 km/litre						
Total - g/km	2.82	0.174	4.55	28.81	0.006	466
Exhaust	2.82	0.174	3.01	28.81	0.006	466
Evaporative		0	0.9			
Refuelling		0	0.34			
Running loss		0	0.29			
g/kg fuel	19.19	1.18	30.97	196.09	0.04	3172
g/MJ	0.44	0.0269	0.70	4.46	0.0009	69.3
Uncontrolled; Assumed Fuel Economy: 5.1 km/litre						
Total - g/km	2.63	0.174	8.54	44.55	0.006	466
Exhaust	2.63	0.174	4.98	44.55	0.006	466
Evaporative		0	2.92			
Refuelling		0	0.32			
Running loss		0	0.32			
g/kg fuel	17.90	1.18	58.13	303.23	0.04	3172 –
g/MJ[2]	0.41	0.057	1.32	6.89	0.0009	69.3

[1] Recent measurement results (De Soete, 1993, Ballantyne, et al., 1994) have shown that N_2O emissions from aged catalysts, e.g., tested after driving 15,000 - 25,000 km, are substantially higher than from new catalyst-equipped cars. Tests on comparable models show aged catalysts emitting from roughly 30% more to almost 5 times the rate of new equipment. As indicated in Box 3, Environment Canada has used a value almost 5 times as high for aged catalysts in its national inventory calculations.

[2] Berdowski, et al., (1993*a*) suggest a CH_4 emission factor of 0.057 g/MJ for this vehicle/technology class

TABLE 1-22
ESTIMATED EMISSION FACTORS FOR US HEAVY-DUTY GASOLINE VEHICLES

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Three-Way Catalyst Control;[1] Assumed Fuel Economy: 2.9 km/litre						
Total - g/km	2.64	0.099	1.57	8.43	0.006	832
Exhaust	2.64	0.099	0.689	8.43	0.006	832
Evaporative			0.323			
Refuelling			0.342			
Running loss			0.22			
g/kg fuel	10.07	0.38	5.99	32.16	0.02	3172
g/MJ	0.23	0.01	0.14	0.73	0.0005	69.3
Non-Catalyst Control; Assumed Fuel Economy: 2.8 km/litre						
Total - g/km	3.45	0.174	5.04	40.23	0.006	843
Exhaust	3.45	0.174	2.16	40.23	0.006	843
Evaporative			2.2			
Refuelling			0.36			
Running loss			0.32			
g/kg fuel	12.98	0.65	8.12	151.32	0.02	3172
g/MJ	0.29	0.01	0.18	3.44	0.0005	69.3
Uncontrolled; Assumed Fuel Economy: 2.0 km/litre						
Total - g/km	5.71	0.373	18.16	143.14	0.009	1.165
Exhaust	5.71	0.373	11.54	143.14	0.009	1.165
Evaporative			5.74			
Refuelling			0.55			
Running loss			0.32			
g/kg fuel	15.54	1.02	49.44	389.68	0.02	3172
g/MJ[2]	0.35	0.02	1.12	8.86	0.0005	69.3

[1] Recent measurement results (De Soete 1993, Ballantyne, et al., 1994) have shown that N_2O emissions from aged catalysts, e.g., tested after driving 15 000 - 25 000 km, are substantially higher than from new catalyst-equipped cars. Tests on comparable models show aged catalysts emitting from roughly 30% more to almost 5 times the rate of new equipment. As indicated in Box 3 Environment Canada has used a value almost 5 times as high for aged catalysts in its national inventory calculations.

[2] Berdowski, et al. (1993b) suggest a CH_4 emission factor of 0.057 g/MJ for this vehicle/technology class.

TABLE 1-23
ESTIMATED EMISSION FACTORS FOR US DIESEL[1] PASSENGER CARS

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Advanced Control; Assumed Fuel Economy: 10.6 km/litre						
Total - g/km	0.65	0.01	0.29	0.86	0.007	258
g/kg fuel	8.04	0.12	3.59	10.64	0.08	3188
g/MJ	0.19	0.003	0.084	0.25	0.0019	73.3
Moderate Control; Assumed Fuel Economy: 6.8 km/litre						
Total - g/km	0.93	0.01	0.29	0.86	0.010	403
g/kg fuel	7.36	0.08	2.30	6.81	0.08	3188
g/MJ	0.17	0.002	0.054	0.16	0.0019	73.3
Uncontrolled; Assumed Fuel Economy: 5.1 km/litre						
Total - g/km	1.02	0.01	0.52	1.06	0.014	537
g/kg fuel	6.05	0.06	3.09	6.29	0.08	3188
g/MJ	0.14	0.001	0.073	0.15	0.0019	73.3

[1] Berdowski, et al., (1993*a*) suggest a CH_4 emission factor of 0.005 g/MJ for 4-stroke, 3-way catalyst diesel engines.

TABLE 1-24
ESTIMATED EMISSION FACTORS FOR US LIGHT-DUTY[1] DIESEL TRUCKS

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Advanced Control; Assumed Fuel Economy: 7.7 km/litre						
Total - g/km	0.76	0.01	0.42	0.98	0.009	358
g/kg fuel	6.77	0.09	3.74	8.73	0.08	3188
g/MJ	0.16	0.0021	0.09	0.21	0.0019	73.3
Moderate Control; Assumed Fuel Economy: 5.1 km/litre						
Total - g/km	1.04	0.01	0.42	0.98	0.014	537
g/kg fuel	6.17	0.06	2.49	5.82	0.08	3188
g/MJ	0.15	0.0014	0.06	0.14	0.0019	73.3
Uncontrolled; Assumed Fuel Economy: 4.3 km/litre						
Total - g/km	1.45	0.02	0.83	1.61	0.017	559
g/kg fuel	7.17	0.10	4.11	7.96	0.08	3188
g/MJ	0.17	0.00	0.10	0.19	0.0019	73.3

[1] Berdowski, et al., (1993*a*) suggest a CH_4 emission factor of 0.005 g/MJ for 4-stroke, 3-way catalyst diesel engines

TABLE 1-25
ESTIMATED EMISSION FACTORS FOR US HEAVY DUTY DIESEL[1] VEHICLES

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Advanced Control; Assumed Fuel Economy: 2.8 km/litre						
Total - g/km	5.01	0.06	1.26	6.8	0.025	982
g/kg fuel	16.27	0.19	4.09	22.09	0.08	3188
g/MJ	0.38	0.005	0.10	0.52	0.0019	73.3
Moderate Control; Assumed Fuel Economy: 2.8 km/litre						
Total - g/km	11.94	0.07	1.7	8.28	0.025	991
g/kg fuel	38.41	0.23	5.47	26.64	0.08	3188
g/MJ	0.90	0.01	0.13	0.63	0.0019	73.3
Uncontrolled; Assumed Fuel Economy: 2.2 km/litre						
Total - g/km	16.79	0.1	2.99	8.54	0.031	1249
g/kg fuel	42.86	0.26	7.63	21.80	0.08	3188
g/MJ	1.01	0.01	0.18	0.51	0.0019	73.3

[1] Berdowski, et al., (1993*a*) suggest a CH_4 emission factor of 0.005 g/MJ for 4-stroke, 3-way catalyst diesel engines

TABLE 1-26
ESTIMATED EMISSION FACTORS FOR US MOTORCYCLES

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Non-catalytic Control; Assumed Fuel Economy: 14.9 km/litre						
Total - g/km	0.53	0.15	2.2	13.2	0.002	160
g/kg fuel	10.52	2.98	42.9	261	0.04	3188
g/MJ	0.24	0.07	0.97	5.9	0.0009	69.3
Uncontrolled; Assumed Fuel Economy: 12.8 km/litre						
Total - g/km	0.19	0.329	6.5	23.8	0.002	186
g/kg fuel	3.23	5.60	111	405	0.04	3172
g/MJ	0.07	0.13	2.5	9.2	0.0009	69.3

European Emission Estimates

The European emission estimates for NO_x, CH_4, NMVOC (total VOC minus CH_4), CO, N_2O and CO_2 are based on the COPERT90 model, developed for the Commission of the European Communities.[20] The calculation is based on five main types of input parameters

- total fuel consumption
- vehicle park
- driving condition

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[20] As is the convention throughout these *Guidelines*, CO_2 emissions are calculated to include the carbon emitted as CO and as VOC. The rationale for this approach is explained in the Introduction.

- emission factors
- other parameters

For these main types of input parameters, additional information (e.g., on vehicle classes, production years etc.) is needed in order to carry out the calculations.

The methodology is defined in such a way that it uses the firm technical data and that national variations among Member States can be incorporated. The variations may include such things as composition of vehicle park, vehicle age, driving patterns, some fuel parameters and a few climatic parameters. Other variations which may exist, for example, variations in vehicle maintenance, mountain driving etc., are not accounted for because there is not enough data available to do so.

Vehicle category split

The vehicle category split required by CORINAIR 1990 does not meet all aspects of vehicle emissions considered important by the working group. In particular the age of vehicle (year of production) and the engine technology is not sufficiently reflected. Thus, for the purpose of the COPERT work only, a more detailed vehicle category split has been developed.

Hot Emissions

These emissions depend on a variety of factors including the distance that each vehicle travels, its speed (or road type), its age and engine size.

The basic formula for estimating hot emissions using experimentally obtained emission factor is:

Emissions [g] = emission factor [g/km] · vehicle kilometres per year [km]

The emission factors and vehicle kilometres are in most cases split into certain classes of road types and vehicle categories.

However, for many countries the only data known with any certainty are the total fuel consumption of petrol, diesel and LPG, not vehicle kilometres. It is therefore suggested that fuel consumption data are used to check vehicle mileage where they are known and to make a final fuel balance.

Cold Start Emissions

Cold starts, compared with the "hot emissions", result in additional emissions. They take place under all three driving conditions, but seem to be most likely for urban driving. In principle they occur for all vehicle categories. However, emission factors are only available or can be reasonably estimated for gasoline, diesel and LPG passenger cars and - assuming that these vehicles behave like passenger cars - light duty vehicles, so that just these categories are covered by the methodology. Moreover, they are considered not to be a function of vehicle age.

These emissions are calculated as an extra emission over the emissions that would be expected if all vehicles had only hot engines. A factor, the ratio of hot to cold emissions, is used and applied to the fraction of kilometres driven with hot to cold engines. These factors may vary from country to country. Different driving behaviour (varying trip lengths), as well as climate with varying time (and hence distance) required to warm up the engine affect the fraction of distance driven with cold engines. These factors can be taken into account, but again information may not be available to do this thoroughly in all countries, so that estimates have to close identified gaps.

Evaporative VOC Emissions

There are three primary sources of evaporative emissions from vehicles:

i) diurnal (daily) emissions;
ii) hot soak emissions; and
iii) running losses.

These are estimated separately. Again they are affected by factors that vary from country to country.

All three types of evaporative emissions are significantly affected by the volatility of the gasoline being used, the absolute ambient temperature and temperature changes, and vehicle design characteristics. For hot soak emissions and running losses the driving pattern is also of importance.

In general, the estimation of evaporative emissions from gasoline vehicles involves still a large number of uncertainties which can not be solved without carrying out further measurements. Therefore the 1990 methodology cannot overcome many of the problems, but can try only to improve on some specific aspects.

Application of the baseline methodology to the different vehicle categories and pollutants

Due to gaps in knowledge, the baseline methodology can not be applied in full and in the same way to all vehicle categories. Moreover, there are variations depending on the pollutant considered. In general, one can distinguish between four methods:

Method A *Hot emissions* are calculated based on:

- the total annual kilometres driven per vehicle;
- the share of kilometres driven under the driving modes "urban", "rural" and "highway";
- the average speed of the vehicles under the driving modes "urban", "rural" and "highway";
- speed-dependent hot emission factors.

Cold start emissions are calculated based on

- the average trip length per vehicle trip;
- the average monthly temperature;
- temperature and trip length dependent cold start correction factor.

Evaporative emissions are calculated based on

- the fuel volatility (RVP);
- the average monthly temperature and the average monthly temperature variation;
- fuel volatility and temperature dependent emission factors.

Method B: The total annual emissions per vehicle are calculated based on:

- the total annual kilometres driven per vehicle;
- the share of kilometres driven under the driving modes "urban", "rural" and "highway";
- the average speed of the vehicles under the driving modes "urban", "rural" and "highway";
- speed-dependent emission factors.

Note: for diesel passenger cars, cold start extra emissions for CO, NO_X and NMVOC, as well as extra fuel consumption, are added using the method described under A. For LPG passenger cars a simplified method is used.

Method C The total annual emissions per vehicle are calculated based on:

- the total annual kilometres driven per vehicle;
- the share of kilometres driven under the driving modes "urban", "rural" and "highway";
- driving mode dependent emissions factors.

Note: for gasoline and diesel light-duty vehicle, cold start extra emissions for CO, NO_X and NMVOC, as well as fuel consumption, are added using the method described under A. For gasoline light-duty vehicles, NMVOC evaporative emissions are added using the method described under A.

Method D: The total annual emissions per vehicle category are calculated based on:

- the total annual fuel consumption of the vehicle category and/or the total annual kilometres driven by the vehicle category;
- fuel consumption and/or kilometre related emission factors.

Note: For two wheelers NMVOC evaporative emissions are added using the method described under A.

TABLE 1-27

SUMMARY OF PRECISION INDICATORS OF THE EMISSION ESTIMATES AND OF CALCULATION METHODS APPLIED FOR THE DIFFERENT VEHICLE CATEGORIES AND POLLUTANTS
(A, B, C, D: Method Indicators - 1, 2, 3, 4: Precision Indicators)

Vehicle Category	NO_X	CO	NMVOC	CH_4	N_2O	CO_2	Fuel
Passenger Cars							
Gasoline	A/1	A/1	A/1	C/1	C/3	D/1	A/1
Diesel	B/1	B/1	B/1	C/2	C/3	D/1	B/1
LPG	B/1	B/1	B/1	-	-	D/1	B/1
Two stroke	C/2	C/2	C/2	C/4	C/4	D/2	C/2
Light-Duty Vehicles	C/1	C/1	C/1	C/3	D/4	D/1	C/1
Heavy-Duty Vehicles	C/2	C/2	C/2	C/4	D/4	D/2	C/2
Two Wheelers	D/2	D/2	D/2	D/4	-	D/2	D/2
Evaporation							
Passenger Cars	-	-	A/3[a]	-	-	-	-
Light-Duty Vehicles	-	-	C/4[a]	-	-	-	-
Two Wheelers	-	-	D/4	-	-	-	-
Cold Start							
Passenger Cars							
Conventional Gas	A/2	A/2	A/2	-	-	A/2	A/2
Catalyst Gasoline	A/3	A/3	A/3		-	A/2	A/3
Diesel	A/3	A/3	A/3	-	-	A/3	A/3
LPG	B/3	B/3	B/3	-	-	B/3	B/3
Light Duty Vehicles	C/4	C/4	C/4	-	-	C/4	C/4

1 Statistically significant emission factors based on a sufficiently large set of measured and re-evaluated data

2: Emission factors non-statistically significant based on a small set of measured and re-evaluated data

3. Emission factors estimated on the basis of available literature

4 Emission factors estimated applying similarity considerations and/or extrapolation

a Only for gasoline engined vehicles

For the purpose of these IPCC Guidelines for National Greenhouse Gas Inventories, the emission factors from the COPERT model are presented using the American vehicle and control type categories, for ease of comparison. The emission factors have been calculated using data from 10 EU countries. That means the vehicle usage pattern, such as average speed and amount of cold starts, climatical conditions like the monthly average temperature, and the fuel characteristics of these countries are incorporated in the figures. The emission factors provided are therefore valid for an average Western European situation.

TABLE 1-28
EUROPEAN EMISSION CONTROL TECHNOLOGY TYPES AND MODEL YEARS USED TO REPRESENT THEM

TECHNOLOGY	MODEL YEAR
PASSENGER CARS	
Gasoline	
Uncontrolled	1970
Early non-catalyst controls	1971-1979
Non-catalyst controls	1980-1985
Oxidation catalyst	1986-1990
Three-way catalyst	1990-1993

TABLE 1-29
ESTIMATED EMISSION FACTORS FOR EUROPEAN GASOLINE PASSENGER CARS

	EMISSIONS					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
Uncontrolled: Assumed Fuel Economy 8.6 km/l						
Total **g/km**	2.19	0.080	4.63	49.97	0.005	264.15
Exhaust	2.19	0.080	3.54	49.97	0.005	264.15
Evaporative*			1.09			
g/kg fuel	24.94	0.914	52.87	570.31	0.057	3014.5
g/MJ	0.57	0.021	1.22	13.11	0.001	69.30
Early non-catalyst controls: Assumed Fuel Economy 10.6 km/l						
Total g/km	2.05	0.082	3.86	28.57	0.005	212.48
Exhaust			2.49			
Evaporative*			1.37			
g/kg fuel	29.10	1.164	54.80	405.38	0.071	3014.5
g/MJ	0.67	0.027	1.26	9.32	0.002	69.30
Non-catalyst controls: Assumed Fuel Economy 11.8 km/l						
Total **g/km**	2.34	0.071	3.26	19.39	0.005	191.29
Exhaust	2.34	0.071	2.02	19.39	0.005	191.29
Evaporative*			1.24			
g/kg fuel	36.83	1.126	51.40	305.54	0.079	3014.5
g/MJ	0.85	0.026	1.18	7.02	0.002	69.30
Oxidation catalyst: Assumed Fuel Economy 12.3 km/l						
Total **g/km**	1.35	0.071	1.00	7.52	0.005	182.89
Exhaust	1.35	0.071	0.56	7.52	0.005	182.89
Evaporative*			0.44			
g/kg fuel	22.28	1.178	16.49	123.97	0.082	3014.5
g/MJ	0.51	0.027	0.38	2.85	0.002	69.30
Three-way catalyst: Assumed Fuel Economy 11.6 km/l						
Total **g/km**	0.52	0.020	0.38	2.86	0.050	193.34
Exhaust	0.52	0.020	0.32	2.86	0.050	193.34
Evaporative*			0.06			
g/kg fuel	8.03	0.312	5.98	44.59	0.780	3014.5
g/MJ	0.18	0.007	0.14	1.03	0.018	69.30
2-stroke: Assumed Fuel Economy 9.2 km/l						
Total **g/km**	0.76	0.077	10.91	12.04	0.005	245.37
Exhaust	0.76	0.077	9.86	12.04	0.005	245.37
Evaporative*			1.05			
g/kg fuel	9.37	0.946	134.03	147.89	0.061	3014.5
g/MJ	0.22	0.022	3.08	3.40	0.001	69.30

* Including diurnal, soak and running losses

TABLE 1-30
ESTIMATED EMISSION FACTORS FOR EUROPEAN DIESEL PASSENGER CARS

	EMISSIONS					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
Moderate control: Assumed Fuel Economy 13.7km/l						
Total **g/km**	0.66	0.005	0.19	0.71	0.010	190.52
g/kg fuel	10.98	0.083	3.09	11.74	0.165	3148.1
g/MJ	0.26	0.002	0.07	0.28	0.004	74.07

TABLE 1-31
ESTIMATED EMISSION FACTORS FOR EUROPEAN DIESEL LIGHT-DUTY VEHICLES

	EMISSIONS					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
Moderate control: Assumed Fuel Economy 9.2km/l						
Total **g/km**	1.43	0.005	0.42	1.57	0.017	284.07
g/kg fuel	15.89	0.055	4.64	17.44	0.188	3148.1
g/MJ	0.37	0.001	0.11	0.41	0.004	74.07

TABLE 1-32
ESTIMATED EMISSION FACTORS FOR EUROPEAN DIESEL HEAVY-DUTY VEHICLES

	EMISSIONS					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
Moderate control: Assumed Fuel Economy 3.3km/l						
Total **g/km**	10.56	0.063	1.99	8.89	0.030	784.04
g/kg fuel	42.41	0.252	7.98	35.69	0.120	3148.1
g/MJ	1.00	0.006	0.19	0.84	0.003	74.07

TABLE 1-33
ESTIMATED EMISSION FACTORS FOR EUROPEAN GASOLINE LIGHT-DUTY VEHICLES

	Emissions					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
Moderate control: Assumed Fuel Economy 7.3 km/l						
Total g/km	2.94	0.081	4.86	37.12	0.006	308.9
Exhaust	2.94	0.081	3.55	37.12	0.006	308.9
Evaporative*			1.31			
g/kg fuel	28.70	0.790	47.40	362.23	0.059	3014.5
g/MJ	0.66	0.018	1.09	8.33	0.001	69.3

TABLE 1-34
ESTIMATED EMISSION FACTORS FOR EUROPEAN GASOLINE HEAVY-DUTY VEHICLES

	Emissions					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
Uncontrolled: Assumed Fuel Economy 4.4km/l						
Total g/km	6.76	0.110	5.38	58.53	0.006	516.92
Exhaust	6.76	0.110	5.38	58.53	0.006	516.92
Evaporative*						
g/kg fuel	39.41	0.640	31.35	341.36	0.035	3014.5
g/MJ	0.91	0.015	0.72	7.85	0.001	69.30

TABLE 1-35
ESTIMATED EMISSION FACTORS FOR EUROPEAN MOTORCYCLES

	Emissions					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
	MOTORCYCLES < 50 CC					
Uncontrolled: Assumed Fuel Economy 41.7km/l						
Total g/km	0.05	0.100	6.19	9.98	0.001	54.29
Exhaust	0.05	0.100	5.89	9.98	0.001	54.29
Evaporative*			0.39			
g/kg fuel	2.78	5.552	343.92	554.22	0.056	3014.5
g/MJ	0.06	0.128	7.91	12.74	0.001	69.30
	MOTORCYCLES > 50 CC 2 STR					
Uncontrolled: Assumed Fuel Economy 14.9km/l						
Total g/km	0.08	0.150	15.39	21.97	0.002	90.63
Exhaust	0.08	0.150	14.84	21.97	0.002	90.63
Evaporative*			0.55			
g/kg fuel	2.66	4.988	511.94	730.76	0.067	3014.5
g/MJ	0.06	0.115	11.77	16.80	0.002	69.30
	MOTORCYCLES > 50 CC 4 STR					
Uncontrolled: Assumed Fuel Economy 19.6 km/l						
Total g/km	0.30	0.200	3.35	20.00	0.002	114.61
Exhaust	0.30	0.200	2.80	20.00	0.002	114.61
Evaporative*			0.55			
g/kg fuel	7.89	5.261	88.03	526.06	0.053	3014.5
g/MJ	0.181	0.121	2.024	12.093	0.001	69.30

* Including diurnal, soak and running losses

1.6.3.2 Road Vehicles - Alternative Fuels

Alternative motor vehicle fuels such as natural gas, liquefied petroleum gas (LPG), methanol and ethanol are presently being used in a limited way, and are the subjects of a great deal of research and development effort aimed at increasing their usage in the future. This section presents some preliminary estimates of the emissions to be expected from vehicles using these fuels, based on fuel properties and the limited emissions data available.[21]

Natural gas

Because natural gas is mostly methane, natural gas vehicles (NGVs) have lower exhaust NMVOC emissions than gasoline vehicles, but higher emissions of methane. There are no evaporative or running-loss emissions, while refuelling emissions and cold-start emissions are lower. These conditions reduce both NMVOC and CO emissions relative to gasoline vehicles. CO_2 emissions from NGVs will be lower than for gasoline vehicles, since natural gas has a lower carbon content per unit of energy. It is possible to attain increased efficiency by increasing the compression ratio. Optimised heavy-duty NGV engines can approach diesel efficiency levels. NO_x emissions from uncontrolled NGVs may be higher or lower than comparable gasoline vehicles, depending on the engine technology. NO_x emissions from NGVs are more difficult to control using three-way catalysts. N_2O emissions from NGVs were not included.

Table 1-36 shows three types of NGVs: passenger cars, gasoline-type heavy-duty vehicles, and diesel-type heavy-duty vehicles.[22] Two sets of emission factors are shown for each: uncontrolled (typical of a simple natural gas conversion, without catalytic converter or optimisation for emissions) and advanced control (reflecting an engine and catalytic converter factory-produced and optimised for natural gas). The estimates for the passenger car and gasoline-type heavy-duty vehicle are based on a gasoline-type engine, converted to use natural gas. For the uncontrolled vehicles, no changes in the engine are assumed beyond the fitting of a natural gas mixer and modified spark timing such that the efficiency would be the same. For the vehicles with advanced control, a higher compression ratio is assumed to give 15 per cent better fuel efficiency.

For the diesel-type heavy-duty vehicles, the engine assumed is a diesel-type engine converted to lean, Otto-cycle operation using natural gas. The uncontrolled case reflects no further optimisation beyond the conversion, while the controlled case includes extensive combustion optimisation for NO_x control and an oxidation catalytic converter.

Liquefied petroleum gas

LPG is primarily propane (or a propane/butane mixture) rather than methane which affects the composition of exhaust VOC emissions, but otherwise it similar to natural gas Evaporative and refuelling emissions are virtually zero, and CO and exhaust NMVOC emissions are usually lower than gasoline vehicles. The CO_2 emissions should be somewhat lower than gasoline, due to the lower carbon-energy ratio, and the higher octane level allows some increase in efficiency, although less than for natural gas. NO_x emissions from LPG vehicles tend to be higher than for gasoline, but can also be controlled using three-way catalysts. N_2O emissions were not included.

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[21] Actual emission levels from these vehicles may be very different, and further testing is needed to confirm these estimates.

[22] The emissions considered are only those of the vehicle itself - additional emissions due to, e.g., compression or liquefaction of gas for storage on the vehicle, leakage from pipelines, etc. are not included, nor are the potential emissions credits due to, e.g., production of methane from biomass. This is consistent with the treatment of emissions from vehicles using oil-based fuels.

Table 1-37 shows two types of LPG vehicles. The engines and technologies considered are the same as those for natural gas, except that the lean, diesel-derived natural gas engine with propane is not considered.

Methanol and Ethanol

The two alcohols have similar properties, and are discussed together. Development efforts have focused primarily on mixtures of alcohols with gasoline, in flexible fuel vehicles, capable of running on any combination of gasoline and up to 85 per cent methanol or ethanol. Engines and emission control systems are similar to those for advanced-technology gasoline vehicles, and the overall energy efficiency and emissions properties are similar. Table 1-39 shows estimated emissions for a vehicle of this type using M85 (85% methanol/15% gasoline) fuel. Also shown are some rough emissions estimates for heavy-duty vehicles equipped with methanol or ethanol engines.

TABLE 1-36
ESTIMATED EMISSION FACTORS FOR US LIGHT- AND HEAVY-DUTY NATURAL GAS VEHICLES

	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Passenger Cars						
Advanced Control; Assumed Fuel Economy: 14.9 km/m^3						
g/km	0.5	0.7	0.05	0.3	N/A	133
g/kg fuel	10.3	14.5	1.0	6.2	N/A	2750
g/MJ	0.21	0.29	0.02	0.12	N/A	56.1
Uncontrolled; Assumed Fuel Economy: 6.5 km/m^3						
g/km	2.1	3.5	0.5	4.0	N/A	305
g/kg fuel	19.0	31.6	4.5	36.1	N/A	2750
g/MJ	0.38	0.63	0.09	0.72	N/A	56.1
Heavy-Duty Vehicles: Stoichiometric Engine (compare with gasoline)						
Advanced Control; Assumed Fuel Economy: 3.6 km/m^3						
g/km	2.6	3.0	0.20	1.0	N/A	550
g/kg fuel	13.0	15.0	1.0	5.0	N/A	2750
g/MJ	0.26	0.30	0.02	0.10	N/A	56.1
Uncontrolled; Assumed Fuel Economy: 2.2 km/m^3						
g/km	5.7	10.0	1.4	12.0	N/A	900
g/kg fuel	17.4	30.6	4.3	36.7	N/A	2750
g/MJ	0.35	0.61	0.09	0.73	N/A	56.1
Heavy-Duty Vehicles: Lean Burn Engine (compare with diesel)						
Advanced Control; Assumed Fuel Economy: 2.4 km/m^3						
g/km	4.0	4.0	0.40	1.5	N/A	825
g/kg fuel	13.3	13.3	1.3	5.0	N/A	2750
g/MJ	0.27	0.27	0.03	0.10	N/A	56.1
Uncontrolled; Assumed Fuel Economy: 2.0 km/m^3						
g/km	23.0	10.0	2.0	8.0	N/A	990
g/kg fuel	63.9	27.8	5.6	22.2	N/A	2750
g/MJ	1.28	0.56	0.11	0.44	N/A	56.1

TABLE 1-37
ESTIMATED EMISSION FACTORS FOR US LIGHT- AND HEAVY-DUTY LPG VEHICLES.

	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Passenger Cars						
Advanced Control						
g/km	0.5	0.03	0.25	0.3	N/A	170
g/kg fuel	8.8	0.6	4.4	5.3	N/A	3000
g/MJ[1]	0.19	0.01	0.10	0.11	N/A	63.1
Uncontrolled						
g/km	2.1	0.18	3.5	8.0	N/A	356
g/kg fuel	17.7	1.5	29.5	67.5	N/A	3000
g/MJ	0.38	0.03	0.64	1.45	N/A	63.1
Heavy-Duty Vehicles: Stoichiometric Engine (compare with gasoline)						
Advanced Control						
g/km	2.6	0.15	0.70	1.0	N/A	695
g/kg fuel	11.2	0.6	3.0	4.3	N/A	3000
g/MJ	0.24	0.01	0.07	0.09	N/A	63.1
Uncontrolled						
g/km	5.7	0.4	8.0	24.0	N/A	1020
g/kg fuel	16.8	1.2	23.5	70.6	N/A	3000
g/MJ	0.36	0.03	0.51	1.52	N/A	63.1

[1] Berdowski, et al. (1993) suggest a CH_4 emission factor of 0.013 g/MJ for this vehicle/technology class

TABLE 1-38
ESTIMATED EMISSION FACTORS FOR
EUROPEAN LPG PASSENGER CARS

	EMISSIONS					
	NO_x	CH_4	VOC	CO	N_2O	CO_2
Moderate control: Assumed Fuel Economy 8.9km/l*						
Total g/km	2.16	0.056	1.51	7.17	0.000	170.74
g/kg fuel	36.79	0.959	25.66	122.18	0.000	3000
g/MJ	0.80	0.021	0.56	2.65	0.000	63.1

* Under 5 bar pressure

TABLE 1-39
ESTIMATED EMISSION FACTORS FOR US LIGHT- AND HEAVY-DUTY METHANOL VEHICLES

	EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
Passenger Cars (M85 Fuel)						
Advanced Control						
g/km	0.5	0.02	0.66	3.14	N/A	183
g/kg fuel	4.5	0.2	5.9	28.0	N/A	1632
g/MJ	0.19	0.01	0.25	1.19	N/A	69 7
Heavy-Duty Vehicles - Methanol-Diesel Engine - M100 Fuel						
Advanced Control						
g/km	4.0	0.1	1.50	4.0	N/A	908
g/kg fuel	6.1	0.2	2.3	6.1	N/A	1375
g/MJ	0.30	0 01	0.11	0.30	N/A	68.8

1.6.3.3 Non-Road Mobile Sources

Emission factors are provided for major non-road vehicle source categories including farm and construction equipment, railway locomotives, boats, and ships (all primarily equipped with diesel engines), jet aircraft, and gasoline-fueled piston aircraft in Table 1-40.

Emission factors for diesel engines used in railway locomotives, farm equipment such as tractors and harvesters, construction equipment such as bulldozers and cranes, and diesel boats, are from Weaver (1988). These estimates are specific to the United States, but may be applicable to other regions as well. N_2O emission factors for off-road diesels are assumed to be the same as those for heavy-duty on-highway diesel engines.

Large ocean-going cargo ships are driven primarily by large, slow-speed and medium-speed diesel engines, and occasionally by steam turbines and gas turbines (the latter in high power-weight ratio vessels such as fast ferries and warships). The number of vessels equipped with steam or gas-turbine propulsion is small, however, since these vessels are unable to compete with the more efficient diesels in most applications. The results shown for NO_x and CO are from Hadler (1990)[23]. N_2O emissions for these engines were assumed to be the same, on a fuel-specific basis, as those for other heavy-duty diesels, and VOC emissions from these large diesels are probably negligible.

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[23] Other sources consulted for comparison are Melhus (1990), Bremnes (1990), Alexandersson (1990)

TABLE 1-40
ESTIMATED EMISSION FACTORS FOR US NON-HIGHWAY MOBILE SOURCES

	UNCONTROLLED EMISSIONS					
	NO_x	CH_4	NMVOC	CO	N_2O	CO_2
OCEAN-GOING SHIPS						
g/kg fuel	87	n/a	n/a	1.9	0.08	3212
g/MJ	2.1	n/a	n/a	0.046	0.002	77.4
BOATS						
g/kg fuel	67.5	0.2	4.9	21.3	0.08	3188
g/MJ	1.6	0.005	0.11	0.50	0.002	73.3
LOCOMOTIVES						
g/kg fuel	74.3	0.2	5.5	26.1	0.08	3188
g/MJ	1.8	0.005	0.13	0.61	0.002	73.3
FARM EQUIPMENT						
g/kg fuel	63.5	0.45	9.6	25.4	0.08	3188
g/MJ	1.5	0.011	0.23	0.60	0.002	73.3
CONSTRUCTION AND INDUSTRIAL EQUIPMENT						
g/kg fuel	50.2	0.18	3.9	16.3	0.08	3188
g/MJ	1.2	0.004	0.09	0.38	0.002	73.3
JET AND TURBOPROP AIRCRAFT						
g/kg fuel	12.5	0.1	0.78	5.2	n/a	3149
g/MJ	0.29	0.002	0.018	0.12	n/a	71.5
GASOLINE (PISTON) AIRCRAFT						
g/kg fuel	3.52	2.64	24	1034	0.04	3172
g/MJ	0.08	0.06	0.54	24	0.0009	69.3

Data on emissions from aircraft are limited or presented in forms which are difficult to compare. The factors shown for aircraft were developed by Radian (1990) - for jet (turbine) emissions based on a Pratt and Whitney JT-17 engine (one of the most commonly used types), and for small gasoline-fueled piston aircraft based on a Cessna engine. These are considered very approximate. For the gasoline piston engines, fuel-specific N_2O emissions were assumed to be similar to those for uncontrolled passenger cars.

1.6.4 Data Sources

More detailed emission factors that are representative of the precise vehicle types, control technologies and other conditions in a particular country would always be desirable National experts working on detailed emissions of non-CO_2 GHGs (particularly the indirect gases) should consult the extensive literature on emission factors and estimation procedures which has been developed by other inventory programmes outside of the framework of the IPCC/OECD programme. As distinguished from the illustrative emission factors, these data generally contain more vehicle and control technology detail, and are further broken down by operating conditions (e.g., catalyst vintages, driving cycles). The nature of these assumptions should be known and carefully matched with actual conditions in each country when selecting the specific factors to be used.

Some key examples of data sources are:

- Default Emission Factors Handbook (European Environment Agency Taskforce, 1992)
- CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic, Volume 1: Methodology and Emission Factors (Eggleston, et al., 1992)
- CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic, Volume 2: COPERT Model, Users Mannuel (Andrias, et al., 1992)
- Joint Emission Inventory Guidebook (CORINAIR/EMEP European Environment Agency, 1995 forthcoming)
- US EPA's Compilation of Air Pollutant Emissions Factors: Highway Mobile Vehicles (AP-42), 4th Edition 1985 (US EPA, 1985)
- US EPA's Mobile4 Model and User's Guide. (US NTIS, 1991)
- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987)

1.6.5 Priorities For Future Work

Access to Existing Data: There is a significant amount of past and on-going work in the area of mobile source emissions estimation that could be very useful for all countries. Major references are cited in the previous section. However, at this time there is no simple mechanism which enables published information, and especially underlying databases to be disseminated among other interested countries. The IPCC/OECD Programme should address information exchange more explicitly, in conjunction with other interested organisations and programmes, possibly resulting in a clearinghouse or some other mechanism to improve access to such information.

Data for Non-OECD Regions of the World: Most of the information which does exist on emissions performance of vehicles, is based on data collected in the OECD countries. Measurement data are urgently needed to determine the characteristics of vehicle fleets in non-OECD countries and to develop adjusted emission factors if necessary.

Key Emission Factor Uncertainties: At this moment there are some key areas for which available emission factors are not adequate to support national inventory development. Expert groups have identified several specific categories for priority work:

- CH_4 uncontrolled gasoline road vehicles, particularly as affected by age and maintenance

- N_2O- biofuels for all applications

  ships, aircraft and rail

  gasoline and diesel vehicles (with and without catalyst control)

  LPG, natural gas and biofuels used for road transport (with and without catalyst control)

1.7 Greenhouse Gas Emissions from Burning Traditional Biomass Fuels

1.7.1 Overview

For all burning of biomass fuels, the IPCC methodology requires that net CO_2 emissions are treated as zero in the energy sector. Some biomass fuels are sustainably produced, in which case the actual net emissions are zero. However, even if all or part of the biomass fuel burned is extracted unsustainably from existing biomass stocks (e.g., forests), it would be difficult to determine, at the point of combustion, what fraction actually represents net emissions. Therefore, net CO_2 emissions, which are reflected in reductions in biomass stocks, are accounted for in the Land Use Change and Forestry section of the methodology.[24] However, other (non-CO_2) gases are emitted from burning of biomass fuels. Emissions of these gases (e.g., methane - CH_4, carbon monoxide - CO, nitrous oxide - N_2O, and oxides of nitrogen - NO_x) are net emissions and are accounted for as energy emissions. This section provides a method for calculating emissions of these non-CO_2 gases from burning of traditional biomass fuels.

Non-methane volatile organic compounds (NMVOCs) are also emitted in significant quantities from burning of biomass fuels. These emissions, in principle, can be treated in the same way as other non-CO_2 gases. However, no detailed methods discussion or default values for NMVOCs are provided in this version of the *Guidelines*. This is an area to be considered in future improvements to the *Guidelines*

Burning of "traditional biomass" is intended to include all traditional, small-scale use of biomass fuels, such as cooking stoves and open fires. It also includes the production as well as consumption of charcoal in small-scale traditional processes. In these conditions, emissions can be estimated using emission ratios of CH_4 and other gases to total carbon oxidised in the biomass, as is done in the various non-energy types of open burning Non-CO_2 trace gas emissions from commercial use of biomass in large-scale combustion facilities or other technologies for converting energy, are treated elsewhere in the fuel combustion chapter. This is because the recommended methods for calculating emissions for these source types are different from the method proposed here for traditional, small-scale bioenergy use. Emissions from large-scale facilities are very much a function of the particular technology used and are treated like emissions from stationary fossil fuel combustion – with emission factors for each of the technology/fuel combinations Emissions from traditional biomass fuel use also vary significantly according to technology, operating conditions, etc However, available data often do not support a technology-specific approach for traditional biomass fuel use. Therefore, the emission ratios approach is provided as a common method for rough estimation which can be used by all national experts.

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[24] For policy analysis purposes in the energy sector, it may be very important to consider the net CO_2 emissions from biomass fuel burning as an energy-related emission This can facilitate the comparison of biomass fuel combustion with other energy options on the basis of CO_2 or total GHG emissions. It is possible to reallocate the implied CO_2 emissions to biomass burning for such analytic purposes. However, it is essential, for consistency, that all **national inventories** be reported as specified in the *IPCC Guidelines*, that is, no net CO_2 emissions are counted for biomass burning.

This separation between commercial and traditional biomass does introduce the possibility of double counting some biomass energy use. Care should be taken to ensure that the "commercial" component of bioenergy use is carefully defined and deducted from total bioenergy consumed before doing the calculations of emissions from traditional biomass fuel use described in this section. It should also be noted that other possibilities for double counting of emissions from biomass fuels exist in the methodology. Agricultural residues and dung are two of the traditional fuels included in this section. Both are also sources of emissions calculated in the agriculture section. Some of the agricultural residues may be burned in the fields and produce the same set of trace gases in that situation. Dung is treated as a potential source of methane emissions from anaerobic decomposition in the calculation of emissions from animal wastes. In both cases it is the responsibility of users of this methodology to ensure that these materials are allocated to their different uses and not counted in both places.

For traditional biomass fuels, the approach is essentially the same as that used for non-CO_2 trace gases from all burning of unprocessed biomass, such as field burning of agricultural residues and savanna burning (Chapter 4: Agriculture) and open burning of cleared forests (Chapter 5: Land Use Change and Forestry). For all these activities there is a common default approach in that rough estimates of non-CO_2 trace gas emissions can be based on ratios to the total carbon released. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. To handle nitrogen trace gases, ratios of nitrogen to carbon in biomass fuels are first used to derive total nitrogen released. Then emissions of N_2O and NO_x are based on ratios to total nitrogen released. Default values for non-CO_2 trace gas emission ratios are provided, including ranges which emphasise their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[25]

1.7.2 Recommended Methodology

Calculations: There are two basic components to the calculation. First, it is necessary to estimate the amount of carbon released to the atmosphere from biomass fuel burning. These carbon releases are not **net** emissions, but are needed to derive non-CO_2 trace gas emissions which are net emissions. The activity data required are the annual consumption[26] of the various types of biomass fuels. Box 4 provides some suggestions for developing these data. Based on the type of fuel burned, the amount of carbon released can be calculated (a reflection of carbon content and fractions oxidised, see Table 1-41). The second component is the same as for other biomass burning categories – emission ratios are applied to estimate the amount of non-CO_2 trace gas released based on the amount of carbon released (Box 5).

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[25] Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible, or to provide some expression of the level of confidence associated with various point estimates provided in the inventory. Procedures for reporting this uncertainty or confidence information are discussed in *Volume 1, Reporting Instructions*.

[26] For all agricultural, forestry and land use change sources and sinks, the general recommendation is to use a three-year average of activity data (e.g., quantity of crop residues burned in fields) rather than a single year's data if possible. For **biomass burned for energy** purposes, however, it is recommended that data for the actual **inventory year** be used, to be consistent with commercial energy statistics.

Step 1: Total Carbon Released. First the mass of fuel, as dry matter, is multiplied by the fraction oxidised in burning to determine the biomass oxidised. Second a carbon fraction is applied to determine the total carbon released. The general equation for estimating carbon emissions is:

Carbon Released from Biomass Fuel
= Total Biomass Consumed (kt dm)
x Fraction Oxidised
x Carbon Fraction

For emissions from charcoal production, a somewhat different procedure is needed. The carbon emitted during production is determined on a mass balance basis, as the difference between the total carbon contained in wood (or other materials) used as input to the charcoal production process and the carbon contained in charcoal produced. The basic formula is:

Emissions from charcoal production =
(fuelwood used in charcoal production x carbon fraction of fuelwood)
– (charcoal produced x carbon fraction of charcoal)

Where credible national statistics exist, they should be used. However, if necessary, it is possible to derive many of the data needed through simple default assumptions. Charcoal consumption can be estimated as discussed in Box 4. It is reasonable to assume that charcoal consumed/produced can be multiplied by a conversion ratio, (fuelwood input in tonnes dry matter to charcoal output in tonnes dry matter), to derive the amount of wood used in charcoal production.

Conversion ratios are highly variable depending on the conditions of the conversion process. Delmas (1993) recommended a ratio of about 4:1 based on one set of measurements. Senelwa and Hall (1993) estimated a national average of more than 6:1 in Kenya. Ratios in the range of 4:1 up to 8:1 may be reasonable depending on average conditions in a country or region. National experts are encouraged to carefully consider the typical conversion processes used in their countries, select a ratio from this range, and explain the reasoning for this ratio.

Once fuelwood input has been derived, the general default carbon fraction (from Table 1-41) can be applied to estimate carbon input. Charcoal consumed/produced can be multiplied by its carbon fraction to estimate total carbon produced. There are a range of values which can be used for carbon fraction of charcoal. Delmas and Ahuja (1993) recommended a default value of 0.87, but a recent experts' workshop (IPCC/OECD, 1994) recommended values in the range of 0.6 to 0.8 for developing countries.

Step 2: Non-CO_2 Trace Gas Emissions. Once the carbon released from biomass fuel burning and charcoal production has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated as follows.[27] The amount of carbon released due to burning is multiplied by the emission ratios of CH_4 and CO relative to total carbon emissions to yield total emissions of CH_4 and CO (each expressed in units of C). The emissions of CH_4 and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights.

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[27] From Crutzen and Andreae, 1990.

BOX 4
FUEL CONSUMPTION ACCOUNTING

For traditional biomass fuel use, direct consumption statistics are often incomplete or unavailable. Large amounts of traditional fuels used may be transacted outside of normal commercial fuel markets. Rather, they may be traded in the informal sector or directly gathered by consumers. In this situation, it is often considered more accurate to base fuel consumption estimates on surveys of patterns of use by households and small commercial users. In many countries, such surveys have produced rules of thumb concerning per capita use of traditional fuels (charcoal, fuelwood, dung, etc.). Survey results may be available as national averages, or broken down between rural and urban populations, or by region within countries. Users of this methodology may determine this to be the most reliable approach for all or part of biomass fuel consumption. In that case, available values for per capita consumption of biomass fuels should be documented and multiplied by population to obtain total consumption values by fuel type.

To calculate emissions of N_2O and NO_x, first the total carbon released is multiplied by the estimated N/C ratio of the fuel by weight (default values for biomass fuels are provided in Table 1-41). Use the fuelwood value for charcoal production to yield the total amount of nitrogen (N) released. The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the N content of the fuel to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28[28] and 46/14, respectively.

The non-CO_2 trace gas emissions from burning calculation is summarised as follows.

CH_4 Emissions = (carbon released) x (emission ratio) x 16/12

CO Emissions = (carbon released) x (emission ratio) x 28/12

N_2O Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 44/28

NO_x Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 46/14

TABLE 1-41
BIOMASS FUELS DEFAULT DATA

Fuel Type	Carbon Fraction[1]	Nitrogen-Carbon (N/C) Ratio[2]	Fraction Oxidised[1]
Fuelwood	0.45-0.5	0.01	0.87
Charcoal Consumption	0.87	'	0.88
Dung	0.36-0.42	'	0.85
Agricultural Residues[3]	0.4-0.48	0.01-0.02	0.88

Sources [1] Delmas and Ahuja, 1993.
[2] Crutzen and Andreae, 1990

Note [3] These are general default values for crop residues. Specific carbon fraction and N/C ratio data for residues from individual crops are provided in the agricultural burning discussion in chapter 4. If consumption data on biomass fuels are available by crop type, then they may be used.

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[28] The molecular weight ratios given above for the emitted gases are with respect to the weight of nitrogen in the molecule. Thus for N_2O the ratio is 44/28 and for NO_x it is 46/14. NO_2 has been used as the reference molecule for NO_x.

Box 5

TRACE GAS EMISSIONS RATIOS

Emissions of CH_4, CO, N_2O and NO_x from burning of traditional biomass fuels (and other types of biomass burning associated with forest clearing and agriculture) are generally estimated by first calculating the total carbon emitted (mostly as CO_2) from combustion and applying a series of ratios. First, a ratio of nitrogen to carbon in fuel is applied to estimate total nitrogen released. Then specific ratios of CH_4 and CO to total carbon, and N_2O and NO_x to total nitrogen are used to estimate these trace gas emissions. Crutzen and Andreae (1990) provided a range of values considered representative of biomass burning generally.

Compound	Ratios	
CH_4	0.01	(0.007 - 0.013)
CO	0.06	(0.04 - 0.08)
N_2O	0.007	(0.005 - 0.009)
NO_x	0.121	(0.094 - 0.148)

Source. Crutzen and Andreae, 1990

More recently, Lacaux et al.(1993) have suggested a lower emissions ratio range for CO: 0.06 (0.04-0.08). It is recommended that this range be used as the default value for CO, rather than the range listed above.

Delmas (1993) and Delmas and Ahuja (1993) have developed ratios for CH_4 from different types of biomass burning, including values for specific biomass fuels and open burning from forest clearing and agriculture. Delmas and Ahuja (1993) also provide a ratio for estimating methane from the charcoal production process. This value is much higher than the Crutzen and Andreae range for relatively open burning, and should be used to estimate what could be a significant methane source in many countries. Fuel values are shown below.

Fuel Type	**Ratio - C-CH_4/total C**
Fuelwood	0.012 (0.009-0.015)
Agricultural Residues	0.005 (0.003-0.007)
Dung	0.017
Charcoal combustion	0.0014
Charcoal production	0.063 (0.04-0.09)

These more recent values are considered more accurate than the Crutzen and Andreae ranges where available for individual components of biomass burning.

Note: Delmas (1993) does **not** provide emission factors for charcoal combustion, and Delmas and Ahuja (1993) provide only a point estimate of 0.0014.

1.8 Fugitive Emissions from Coal Mining and Handling Activities

1.8.1 Overview

This section covers fugitive emissions of greenhouse gases (GHGs) from production, processing, handling and utilisation of coal. Intentional or unintentional releases of gases such as methane in mining are included here, as are emissions from inadvertent combustion of coal in coal mine fires. By far the most important component of this subcategory is methane (CH_4) emissions from the mining and handling of coal. The bulk of this section, therefore, deals with these emissions. Two other fugitive emission sources are discussed briefly at the end of the section. These are burning coal mines and waste piles, which emit CO_2, and SO_2 scrubbing, which is also a source of CO_2. There are very likely other fugitive emissions associated with the coal fuel cycle. If important sources are identified, these will be considered for inclusion in future editions of the *Guidelines*.

1.8.2 CH_4 From Coal Mining And Handling Activities

The process of coal formation, commonly called coalification, inherently generates methane and other by-products. The formation of coal is a complex physio-chemical process occurring over millions of years. The degree of coalification (defined by the rank of the coal) determines the quantity of methane generated and, once generated, the amount of methane stored in the coal is controlled by the pressure and temperature of the coal seam and by other, less well-defined characteristics of the coal. The methane will remain stored in the coal until the pressure on the coal is reduced, which can occur through the erosion of overlying strata or the process of coal mining. Once the methane has been released, it flows through the coal toward a region of lower pressure (such as a coal mine) and into the atmosphere (Boyer, 1990) Methane emissions from coal mining in 1990 contributed an estimated 23 to 39 Tg of methane (US EPA, 1993*a*; CIAB, 1992, Airuni, 1992).

The amount of CH_4 generated during coal mining is primarily a function of coal rank and depth, gas content, and mining methods, as well as other factors such as moisture. Coal rank represents the differences in the stages of coal formation and depends on the pressure and temperature history of the coal seam; high coal ranks, such as bituminous coal, contain more CH_4 than low coal ranks, such as lignite. Depth is important because it affects the pressure and temperature of the coal seam, which in turn determines how much CH_4 is generated during coal formation. If two coal seams have the same rank, the deeper seam will hold larger amounts of CH_4 because the pressure is greater at lower depths, all other things being equal. As a result, the methane emission factors for surface-mined coal are assumed to be lower than for underground mining.

In most underground mines, methane is removed by ventilating large quantities of air through the mine and exhausting this air (typically containing a concentration of 1 per cent methane or less) into the atmosphere In some mines, however, more advanced methane recovery systems may be used to supplement the ventilation systems and ensure mine safety. These recovery systems typically produce a higher concentration product, ranging from 35 to 95 per cent methane. In some countries, some of this recovered methane is used as an energy source, while other countries vent it to the atmosphere. Recent technological innovations are increasing the amount of medium- or high-quality methane that can be recovered during coal mining and the options available to use it. Thus, methane emissions could be reduced from this source in the future.

In surface mines, exposed coal faces and surfaces, as well as areas of coal rubble created by blasting operations, are believed to be the major sources of methane. As in underground mines, however, emissions may come from the overburden (in limited cases where these strata contain gas), which is broken up during the mining process, and underlying strata, which may be fractured and destressed due to removal of the overburden. Because surface-mined coals are generally lower rank and less deeply buried, they do not tend to contain as much methane as underground-mined coals. Thus, emissions per tonne of coal mined are generally much lower for surface mines. Research is underway in the United States and elsewhere to increase the understanding of CH_4 emissions from surface mines (Kirchgessner, 1992; USGS, 1993).

A portion of the CH_4 emitted from coal mining comes from post-mining activities such as coal processing, transportation, and use. Coal processing involves the breaking, crushing, and thermal drying of coal, making it acceptable for sale. Methane is released mainly because the increased surface area allows more CH_4 to desorb from the coal. Transportation of the coal contributes to CH_4 emissions, because CH_4 desorbs directly from the coal to the atmosphere while in transit (e.g., in railroad cars). Use of metallurgical coal also emits methane. For instance, in metallurgical coke production, coal is crushed to a particle size of less than 5 mm, vastly increasing the surface area of the coal and allowing more CH_4 to desorb. During the coking process, methane, carbon monoxide, and other volatile gases are released. In modern coke ovens, this gas is typically collected and used as a fuel source, but in older coke ovens, particularly those used in less developed regions, coke gas is vented to the atmosphere (Boyer, 1990; coke production is covered in Chapter 3).

Some methane is also released from coal waste piles and abandoned mines. Coal waste piles are comprised of rock and small amounts of coal that are produced during mining along with marketable coal. There are currently no emission measurements for this source. Emissions are believed to be low, however, because much of the methane would likely be emitted in the mine and the waste rock would have a low gas content compared to the coal being mined. Emissions from abandoned mines may come from unsealed shafts and from vents installed to prevent the build-up of methane in mines. There is very little information on the number of abandoned mines, and no data are currently available on emissions from these mines. Most available evidence indicates that methane flow rates decay rapidly once deep mine coal production ceases (Williams and Mitchell, 1992, Creedy, 1991). In some abandoned mines, however, methane can continue to be released from the surrounding strata for many years. In Belgium, France, and Germany, for example, several abandoned mines are currently being used as a source of methane which is being added to the gas system (Smith and Sloss, 1992; KfA, 1993). Due to the absence of measurement data for both coal waste piles and abandoned mines, no emissions estimates have been developed for these sources.

Review of Previous Methane Emission Estimation Studies

Over the years, a variety of methane emissions estimates have been developed for coal mining, as shown in Table 1-42. As the table shows, the variation in estimates has been quite large, although more recent studies are showing more similar results. Many of the emission studies conducted to date have confronted difficulties in developing estimation methodologies and these have resulted in the widely varying estimates and large uncertainties. These difficulties include:

TABLE 1-42
SUMMARY OF EMISSIONS ESTIMATES FROM SELECTED STUDIES

Study Author	Emissions Estimate (Tg)	Year of Estimate	Methodological Issues
Koyama (1963)	20	1960	Hard coal only; no emissions estimates for surface mining or post-mining activities. 1960 coal production data.
Hitchcock & Wechsler (1972)	8 - 28	1967	Post-mining not included; source of emission factors, particularly low end, unspecified. 1967 coal production data
Seiler (1984)	30	1975	Based on Koyama, with 1975 coal production data.
Crutzen (1987)	34	NA	Source of emission factors unclear. Hard coal only; no emissions estimates for surface mining or post-mining activities
Okken & Kram (1989)	15 - 45	NA	Source of emission factors unclear. Hard coal only, no emissions estimates for surface mines or post-mining activities
Zimmermeyer (1989)	24	NA	Only underground mining considered; no emissions estimates for surface mines or post-mining activities.
Seltzer & Zittel (1990)	23	NA	Adjusted Zimmermeyer by: (1) including surface mines, (2) assuming that 15 percent of underground mining emissions (3.6 Tg) not emitted to the atmosphere due to methane utilisation
Barns & Edmonds, US DOE (1990)	25	1986	Assumed mathematical relationship between coal rank and depth and that in-situ methane content was equal to the mining emission factor
Boyer, US EPA (1990)	33 - 64	1988	Statistical approach related methane emissions to in situ methane content. Correlation based on US data only. Large uncertainty in application of results for global estimates
Hargraves (1990)	29	NA	Method based on current methane production rates due to continued coalification
Airuni (1992)	28	1990	Methodology unspecified
CIAB (1992)	24	1990	Country specific data used where available for underground mines. Surface and post mining emissions developed using low emission assumptions. No uncertainty analysis
US EPA (1993*a*)	23 - 39	1990	Country specific data used where available for underground mines. Global average emission factors for rest of countries for underground mines and for all surface mining and post mining emissions

- **Absence of data on which to base estimates:** Many studies were developed without access to detailed data on methane emissions associated with various components of the coal cycle. For certain sources such as surface mines and post-mining activities, moreover, reliable emissions measurements are still lacking.
- **Use of national data to develop global estimates:** Some studies have relied on data from a single country to estimate global methane emissions from coal mining This approach can introduce large errors into the estimates, due to the difficulty of generalising from one country's coal characteristics and mining conditions to those of other countries. Mining experience has shown that there are frequently significant differences in methane emission factors within countries, coal basins, and even coal mines for a variety of geological and other reasons.
- **Failure to include all possible emission sources:** Some studies prepared to date have only estimated underground coal mining emissions from ventilation systems and have not included emissions from degasification systems, or post-mining emissions. In addition, many estimates have assumed emissions from surface mines to be negligible and have not included this source. At this point, moreover, there are still potential emission sources, such as abandoned mines, for which emissions cannot be estimated due to the absence of necessary data.
- **Over-reliance on statistical estimation methodologies:** Several studies have estimated global emission factors using statistical models that relate methane emissions to various coal properties. For the most part, these models have proven unreliable when estimates are compared to those developed using more detailed country-specific information. The principal problem with using statistical methodologies is the number of variables that can affect methane emissions. Mining experience has shown that a complete understanding of methane emissions requires detailed examination of coal and geological characteristics and that methane emissions can be highly variable within mines, basins and countries. Collecting comprehensive data and developing statistical models that can reliably predict emissions on a global basis is thus very difficult.

In general, the results of the more recent country-specific and global methane emission studies are likely to be more reliable than previous efforts. For several of the major coal producing countries, for example, detailed data on methane emissions from underground mine ventilation and degasification systems are reported to central institutes and are publicly available. More recent studies have been able to use these data in preparing and validating their estimates of methane emissions from underground mines. Data are still lacking on emissions from surface mines and post-mining activities, thus even the emission estimates from more recent studies should be considered uncertain.

Suggested Emission Estimation Methods

Methane emission estimates should be developed for the three principal sources of methane emissions: underground mines, surface mines, and post-mining activities To assist in developing these estimates, the IPCC recommends use of a "tiered" approach for estimating emissions. For each source, two or more approaches (or "tiers") are presented for estimating emissions, with the first tier requiring basic and readily available data and higher tiers requiring additional data. Selection among the tiers will depend upon the quality of the data available in the country.

1.8.3 Underground Mining

Methane emissions from underground mines should include estimated emissions from ventilation systems and from degasification systems, if any of a country's mines use degasification systems to supplement ventilation. In the approaches outlined below, methods of estimating emissions from both of these sources are presented.

Three possible approaches are suggested by the IPCC, with the choice among them depending upon the availability of data and the degree to which coal mining is considered a significant source of emissions by particular countries. Two of the methods, the "Global" and the "Country or Basin Average" methods are essentially identical in form; only the degree of detail and specificity in choice of emission factor(s) differs. The third, "Mine Specific" method relies on the assembly of methane emission measurements taken at coal mines. In the first two methods, tiers 1 and 2, ranges of emission factors are given in terms of m^3 CH_4/tonne of coal produced. The structure of the estimation is simply

$$\boxed{\begin{array}{c}\text{Emissions (Gg } CH_4) = \text{Emission Factor } (m^3\ CH_4 \text{ / tonne}) \\ \text{x tonnes of coal produced} \\ \text{x Conversion Factor } (Gg/10^6 m^3)\end{array}}$$

A single value from the range of emission factors should be used to prepare the emissions estimate. The relevant coal production figure will be that for the country or the coal basin depending upon the method selected. Factors are given in the table below which permit the conversion of the volume emitted to mass.

For those countries with comparatively large methane emissions from coal mining, the use of more detailed estimation methodologies may be warranted. In countries producing smaller quantities of coal, however, the most simple approach may provide a reasonably accurate first approximation of CH_4 emissions from underground mines.

Tier 1: Global Average Method

The simplest method for estimating methane emissions is to multiply underground coal production by a factor drawn from a range of factors representing global average emissions from underground mining, including both ventilation and degasification system emissions. This method may be selected in cases where total coal production from underground mines is available but more detailed data are not. The Tier 1 Equation is shown below.

EQUATION 1
TIER 1: GLOBAL AVERAGE METHOD – UNDERGROUND MINES

CH_4 Emissions (Gg) = CH_4 Emission Factor (m^3 CH_4/tonne of coal mined)
x Underground Coal Production (Mt)
x Conversion Factor (Gg/10^6 m^3)

Where:

- the Emission Factor should be chosen from the following range

Low CH_4 Emission Factor = 10 m^3/tonne

High CH_4 Emission Factor = 25 m^3/tonne

- Conversion Factor converts the volume of CH_4 to a weight measure and is the density of methane at 20°C and 1 atmosphere, namely:

0.67 Gg / 10^6 m^3

The IPCC recommends revised global average emission factors of 10 to 25 m^3/tonne of coal mined (not including emissions from post-mining activities which should be calculated separately). This range reflects the findings of various country studies, as shown in Table 1-43. As more detailed emissions data are published by various countries, the factors can be further revised, if necessary.

TABLE 1-43
ESTIMATED UNDERGROUND EMISSION FACTORS FOR SELECTED COUNTRIES

Country	Emission Factors (m^3/tonne)	Source
Former Soviet Union	17.8 - 22.2	US EPA, 1993a
United States	11.0 - 15.3	US EPA, 1993b
Germany (East & West)	22.4	Zimmermeyer, 1989
United Kingdom	15.3	BCTSRE, 1992
Poland	6.8 - 12.0	Pilcher, 1991
Czechoslovakia	23.9	Bibler, 1992
Australia	15.6	Lama, 1992

Tier 2: Country or Basin Specific Method

The suggested Tier 2 approach – called the "Country or Basin Specific Method" – can be used to refine the range of emission factors used for underground mining by incorporating some additional country or basin-specific information. Basically, this method enables a country with limited available data to determine a more appropriate and probably narrower range of emission factors for their underground mines. For many countries, it is expected that this range will fall within the global average emission factor range of 10 to 25 m^3/tonne. The range of possible emission factors is not constrained under the Tier 2 approach, however, and some countries may find that their underground mining emission factors lie outside the global average emission factor range. The calculation procedure is identical to that described in Tier 1.

To implement the Tier 2 approach, national experts must examine measurement data from at least a limited number of underground coal mines in their country or region

Using this data, either statistical analysis or expert judgement should be applied to develop a reasonable range of emission factors for the country or region.[29] Making this estimate will require judgement on the part of the estimator as to the adequacy of the available data and its uncertainty If sufficient expertise is not available to make such judgements, it is recommended that the Tier 1 approach (the Global Average Method) be used instead.

In some cases, measurement data on emissions from mines may be unavailable but a country will still seek to develop a narrower estimate based on other types of available data. In such cases, a country may seek to develop a simple emissions model based on physical principles or make judgements based on an evaluation of available data. Among the key types of data that should be considered in such a model or evaluation are.

- the gas content of the coal, which contributes to the total amount of methane available for emission during mining;
- the amount of coal within the strata above and below the mined coal seam, which also contributes to the total amount of methane available for emission during mining and,
- the method of mining, which determines the amount of ground that is disturbed by mining the coal and the extent to which the mining process liberates methane contained in the mined coal seam and in the strata surrounding it.

It should be noted that while the Tier 2 approach can provide some additional information about methane emissions in a particular country or coal basin, the estimates will still be quite uncertain because of the absence of comprehensive and reliable emissions data. This approach should thus be used only in cases where there is a strong need to make an estimate drawn from a narrower range than the Tier 1 (Global Average Method) and not enough data are available to prepare an estimate using the Tier 3 (Mine Specific Method) described in the next section. It should further be noted that an estimate from the narrower range will not necessarily be more accurate than that developed under Tier 1

In all cases where the Tier 2 approach is used, a detailed discussion of the types of data available and the manner used to determine the refined range of emission factors should be presented, so as to allow for the independent verification of the estimate and ensure comparability with estimates being prepared by other countries.

Tier 3: Mine Specific Method

Because methane is a serious safety hazard in underground mines, many countries have collected data on methane emissions from mine ventilation systems, and some also collect data on methane emissions from mine degasification systems. Where such data are available, the more detailed Tier 3 approach – called the "Mine Specific Method" - should provide the most accurate estimate of methane emissions from underground mines Since these data have been collected for safety, not environmental reasons, however, it is necessary to ensure that they account for total emissions from coal mines. The key issues that should be considered when using mine safety data, as well as the recommendations of the IPCC for resolving them, are shown in Table 1-44

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[29] If measurement data is available for most or all or a country's underground coal mines, the Tier 3 approach called the "Mine Specific Method" should be used to estimate emissions.

Treatment of Methane Utilisation

All of the methods described above, with the possible exception of the Mine Specific Method, assume that all of the methane liberated by mining will be emitted to the atmosphere. In many countries, however, some of the methane recovered by mine degasification systems is used as fuel instead of being emitted. Wherever possible, the emission estimates should be corrected for the amount of methane that is used as fuel, by subtracting this amount from total estimated emissions.

In several countries, data on the disposition of methane recovered by degasification systems (i.e., whether it is used or emitted to the atmosphere) can be obtained from the coal industry or energy ministries. Poland, for example, reports that its mine degasification systems recovered 286 million m^3 of methane in 1989, of which 201 million m^3 was used and the remaining 85 million m^3 was emitted to the atmosphere (Polish Central Mining Institute, 1990). Regardless of the method used to develop the emissions estimates, the Polish emission estimate should be adjusted to reflect the use of methane by subtracting 201 million m^3 from total emissions.

In some countries figures for the quantity of gas recovered from mines may not be available from the mining industry. Nevertheless estimates may be constructed if the users of the gas are known and they are able to give data for their consumption. Consumption may also be inferred if it is known that the gas is used to fuel a particular plant of a known capacity (e.g. if the methane is used to fuel a gas turbine of a known size).

TABLE 1-44
KEY ISSUES FOR CONSIDERATION WHEN USING TIER 3 – MINE SPECIFIC METHOD

ISSUE	DESCRIPTION	RECOMMENDATION
Where and how are ventilation system emissions monitored?	When used to develop overall methane emission estimates, the optimal location for ventilation air monitors is at the point where ventilation air exhausts to the atmosphere	If ventilation emissions are not monitored at the point of exhaust, emission data should be corrected based on estimated additional methane emissions between the point of measurement and the point of exhaust to the atmosphere
Are ventilation system emissions monitored and or reported for all mines?	In some countries, emissions are only reported for "gassy mines"	Estimates should be developed for non-gassy mines as well. Estimates can be prepared using information about the definitions of gassy and non-gassy mines and data on the total number of mines and the coal production at these mines
Are methane emissions from degasification systems reported?	Some countries collect and report methane emissions from ventilation and degasification systems, while others only report ventilation system emissions. Both emission sources must be included in emissions estimates	If degasification system emissions are not included, those mines with degasification systems should be identified and estimates prepared on emissions from their degasification systems. Emissions estimates can be based on knowledge about the efficiency of the degasification system in use at the mine or the average efficiency of degasification in the country

The sources of any adjustments to emissions that are made to reflect the utilisation of methane should be clearly specified, to permit the independent verification of the emissions estimates. In the absence of data, estimated adjustments for the use of methane should not be undertaken.

1.8.4 Surface Mining

Two possible approaches for estimating methane emissions from surface mining are suggested by the IPCC. For the most part, these approaches resemble those developed for underground mining, but the results will be much more uncertain due to the absence of emissions data. Methane emissions from surface mining are assumed to arise from two sources: the coal mined and from the surrounding strata exposed during the mining process. In the Tier 1 approach, (Global Average Method) this separation of these sources is ignored and a single emission factor is used. In the Tier 2 approach (Country or Basin Specific Method), emission factors for each source are required. If emissions measurements are developed in the future, it should be possible to refine these methodologies.

Tier 1: Global Average Method

As for underground mining, the simplest Tier 1 approach for surface mines – called the "Global Average Method" – is to multiply surface coal production by an emission factor selected from a global range, within which most emission factors are believed to lie.

EQUATION 2
TIER 1: GLOBAL AVERAGE METHOD – SURFACE MINES

CH_4 Emissions (Gg) = CH_4 Emission Factor (m^3 CH_4/tonne of coal mined)
x Surface Coal Production (Mt)
x Conversion Factor ($Gg/10^6\ m^3$)

Where:

- the Emission Factor should be chosen from the following range:
  Low CH_4 Emission Factor = 0.3 m^3/tonne
  High CH_4 Emission Factor = 2.0 m^3/tonne
- Conversion Factor converts the volume of CH_4 to a weight measure, and is the density of methane at 20°C and 1 atmosphere, namely
  0.67 $Gg/10^6\ m^3$

In the original IPCC methodology, an average emission factor of 2.5 m^3/tonne was recommended (OECD, 1991), based on the results of Boyer (1990) and including emissions from post-mining operations. Based on more recent analyses and additional studies, a revised emission factor range of 0.3 to 2.0 m^3/tonne is recommended by the IPCC, not including post-mining emissions (US EPA, 1993a, CIAB, 1992; BCTSRE, 1992, CMRC, 1990; Kirchgessner, 1993)

Given the lack of information and measurements on methane emissions from surface mines, this range must be considered extremely uncertain, and it should be refined in the future as more data become available

Tier 2: Country or Basin Specific Method

A second tier estimation of methane emissions - called the "Country or Basin Specific Method" – can be used if additional information is available on in-situ methane content and other characteristics of a country's surface-mined coals. This approach enables a country to develop emission factors that better reflect specific conditions in their countries. Depending on the degree of detail desired, emissions can be estimated for specific coal basins or countries, using the equation below

EQUATION 3

TIER 2: COUNTRY OR BASIN SPECIFIC METHOD – SURFACE MINES

CH_4 Emissions (Gg) = [In-Situ Gas Content (m^3 CH_4/tonne)
x Surface Coal Production (Mt)
x Conversion Factor (Gg/10^6 m^3)]
+ [Assumed Emission Factor for Surrounding Strata (m^3 CH_4/tonne)
x Surface Coal Production (Mt)
x Conversion Factor (Gg/10^6 m^3)]

Where:

- In-Situ Gas Content and Assumed Emission Factor for Surrounding Strata are described in the text.
- Conversion Factor converts the volume of CH_4 to a weight measure and is the density of methane at 20°C and 1 atmosphere, namely:

0.67Gg/10^6 m^3

In Equation 3, In-Situ Gas Content represents the methane actually contained in the coal being mined, as determined by measuring the gas content of coal samples. Average values for a coal mine, coal basin or country could be developed, depending on the level of detail in the estimate. For surface mines, unlike underground mines, it is frequently assumed that all of the methane contained in the coal is released during mining and that post-mining emissions from surface-mined coals are effectively zero (BTSCRE, 1992; CIAB, 1992, CMRC, 1990). Some countries may choose to modify this assumption based on their specific conditions. Care should be taken, however, to ensure that any emissions assumed to occur during post-mining activities are subsequently estimated.

Assumed Emission Factor for Surrounding Strata represents the possibility that more methane will be emitted during surface mining than is contained in the coal itself because of emissions from the strata below (or in limited cases, above) the coal seam. Some countries have assumed that there are no emissions from surrounding strata associated with surface-mined coals (BTSCRE, 1992; CMRC, 1990). However, if available information indicates that there are gas-bearing strata surrounding the mined coal seam and that these strata are emitting their gas in conjunction with the mining, countries should include these emissions in their estimates.

Emission factors for the surrounding strata can be developed using one of two approaches. Ideally, the assumed emission factor should be based on an evaluation of the gas content of the surrounding strata and verified by measurements. If such data are unavailable, an alternative method of developing an emission factor is to assume that some multiple of the gas content of the mined coal is emitted by the surrounding strata. It should be noted, however, that the alternative approach is highly speculative given the lack of data upon which to base such an assumption.

1.8.5 Post-Mining Activities

Like surface mining emissions, there are currently few measurements of methane emissions from post-mining activities. In fact, many past studies have overlooked this emission source, while others have developed only rudimentary estimation methodologies. Two possible approaches for estimating emissions from post-mining activities are recommended by the IPCC.

Tier 1: Global Average Method

For the most simple estimates, a global average emission factor can be multiplied by coal production for underground and surface mining, as shown in the equation below. It is important to distinguish between underground- and surface-mined coals because the gas contents are likely to be very different and hence emissions could vary significantly.

EQUATION 4

TIER 1: GLOBAL AVERAGE METHOD – POST-MINING ACTIVITIES

Underground CH_4 Emissions (Gg) = CH_4 Emission Factor (m^3 CH_4/tonne of coal mined)
x Underground Coal Production (Mt)
x Conversion Factor (Gg/10^6 m^3)

Surface CH_4 Emissions (Gg) = CH_4 Emission Factor (m^3 CH_4/tonne of coal mined)
x Surface Coal Production (Mt)
x Conversion Factor (Gg/10^6 m^3)

Where

- Underground CH_4 Emission Factors are in the range of

  0.9 to 4.0 m^3/tonne

- Surface CH_4 Emission Factors are in the range of:

  0 to 0.2 m^3/tonne

- Conversion Factor converts the volume of CH_4 to a weight measure and is the density of methane at 20°C and 1 atmosphere, namely:

  0.67 Gg/10^6 m^3

Underground-Mined Coals The IPCC recommends emission factors of 0.9 to 4.0 m^3/tonne for underground-mined coal, based on recent studies (CIAB, 1992, BC . SRE 1992, US EPA, 1993a)

Surface-Mined Coals Emission factors of 0 to 0.2 m^3/tonne are recommended by the IPCC for post-mining activities involving surface-mined coal (CIAB, 1992, CMRC, 1990 US EPA, 1993a)

Tier 2: Country or Basin Specific Method

Emissions estimates can be refined if additional data are available on coal characteristics. This method may be preferable if higher tier methods have been used to estimate emissions from underground and surface mines. The equation below summarises the approach for preparing refined emission estimates

EQUATION 5

TIER 2: COUNTRY OR BASIN SPECIFIC METHOD – POST-MINING ACTIVITIES

a) Underground CH_4 Emissions (Gg) = In-Situ Gas Content (m^3 CH_4/tonne)
x Underground Coal Production (Mt)
x Fraction of Gas Released During Post-Mining Activities (%)
x Conversion Factor ($Gg/10^6$ m^3)

When Necessary:

b) Surface CH_4 Emissions (Gg) = In-Situ Gas Content (m^3 CH_4/tonne)
x Surface Coal Production (Mt)
x Fraction of Gas Released During Post-Mining Activities (%)
x Conversion Factor ($Gg/10^6$ m^3)

Where:

- In-Situ Gas Content and Fraction of Gas Released During Mining are described in the text
- Conversion Factor converts the volume of CH_4 to a weight measure and is the density of methane at 20°C and 1 atmosphere, namely:

$$0.67\ Gg/10^6\ m^3$$

In-Situ Gas Content represents the methane actually contained in the coal being mined, as determined by measuring gas contents in coal samples. Average values for a coal mine, coal basin or country could be developed, depending on the level of detail in the estimate.

Fraction of Gas Released During Post-Mining Activities represents the percentage of the in-situ gas content that is assumed to be emitted during post-mining activities. There are three key issues related to the estimation of this fraction:

- For Surface-Mined Coal. In most cases, if the Tier 2 approach is used to estimate methane emissions from surface mines, post-mining emissions from surface-mined coals are assumed to be zero. In these cases, the use of Equation 5(b) is unnecessary and countries should be careful to avoid double counting. However, if a country has not assumed that all of the methane contained in surface-mined coal is released during mining, Equation 5(b) should be used to estimate post-mining emissions and the value selected for "Fraction of Gas Released During Post-Mining Activities" should be consistent with the emission factor selected to estimate emissions during surface mining.
- For Underground-Mined Coal: The assumed fractions for underground mining will be based on information about coal permeability, desorption rates, mining methods and other factors. Recent studies have assumed that 25 to 40 percent of the in-situ CH_4 content of underground mined coal is emitted during post-mining activities (US EPA, 1993b; BCTSRE, 1992).
- Fraction of Methane Not Emitted: It is currently assumed that all of the CH_4 contained in mined coal will be emitted to the atmosphere, although it is possible that a fraction could remain in the coal until the point of combustion and be burned instead of emitted. At this time, estimates of the extent to which this may be the

case have not been developed. If countries have such information, however, they could further incorporate this factor into Equation 5.

Total Emissions from Coal Mining Activities

Total methane released as a result of coal mining activities will be the summation of emissions from underground mining (ventilation and degasification systems), surface mining, and post-mining activities. The IPCC recommends that emissions be estimated for each of these categories, in tonnes of CH_4, then aggregated to determine total national methane releases. To the extent that methane that would otherwise have been released to the atmosphere, is recovered and used as fuel, the recovered quantity and its use should be reported and the quantity subtracted from the emission total.

Availability and Quality of Activity Data

Data are readily available to develop general emissions estimates using the Tier I approach – the Global Average Methods – for underground, surface mining as well as post-mining activities. For these estimates, the only data required are country statistics on underground and surface coal production, which are available from domestic sources, such as energy ministries, or from the OECD/IEA, which publishes Coal Information (e.g., 1990).

The IPCC recommends that countries involve their coal mining personnel in the development of emissions estimates as much as possible, because of the improved accuracy of emissions estimates prepared with more detailed coal and mining data. The availability and quality of data collected by mining personnel for mine safety purposes should be assessed on a case-by-case basis, however, to ensure that it can be used appropriately for preparing emissions estimates.

The IPCC further recommends that future efforts attempt to better characterise the factors affecting methane emissions from coal mining for those countries and emission sources with limited data, so as to develop more refined emission factors. Specific activities should include

- Obtaining more data on coal and geological characteristics in selected coal-producing countries.
- Monitoring emissions from surface mines and post-mining activities; and,
- Monitoring emissions from closed or inactive mining operations and some other potential methane sources, such as mine water

1.8.6 CO_2 Emissions From Burning Coal Deposits And Waste Piles

Marland and Rotty (1984) estimated that burning of coal in coal deposits is less than 0.3 per cent of total coal produced and that burning of all coal in waste banks in the United States over a ten year period would represent less than 1 per cent of US coal consumption Subsequently, they chose to ignore these emissions.

If these sources are estimated, the amount of coal burned in waste piles and coal deposits must be specified along with an emission factor that represents the percentage of coal that is carbon times the percentage of carbon oxidised We suggest an arbitrary value of 50 per cent of the carbon present in the coal to represent this emission factor; this value would be highly variable from one country to another and one site to another. This assumption of 50 per cent for an emission factor should be evaluated to determine its validity. The formula for calculating these emissions would be:

EQUATION 6

Emissions from Coal Burning (Gg C) = Quantity of Coal Burned (10^3 t)
x Emission Factor

Where:

- The Emission Factor is: Percentage of Carbon in Coal
x Percentage of Carbon Oxidised;
(and the default value is 50%)

Note that other GHG's such as N_2O, CO, NO_x, etc. are also emitted from combustion of coal wastes.

1.8.7 CO_2 Emissions From SO_2 Scrubbing

When SO_2 scrubbing (or flue gas desulphurisation) technology is used in conjunction with combustion of coal, the process, which removes sulphur dioxide from the flue gas, also releases CO_2 from the chemical reactions during the process. This can be considered a fugitive emission resulting from coal use. Typically, calcium carbonate reacts with sulphur oxides in flue gas to produce calcium sulphate and carbon dioxide. Marland and Rotty (1984) suggest that CO_2 emissions from SO_2 scrubbing are small enough to be ignored in global calculations. However, for completeness, some national experts may wish to include this subcategory.

To estimate carbon emissions from SO_2 scrubbing, the approach is derived from Grubb (1989) with slight modifications. In Grubb's approach, carbon emissions would equal the total amount of coal combusted in plants equipped with scrubbers times the fraction of sulphur by weight in the coal, adjusted for the differences in molecular weight between carbon and sulphur (12/32). Since this procedure assumes that all of the sulphur is removed, it should be adjusted by the sulphur removal efficiency of the desulphurisation process (an average removal efficiency of 90 per cent is suggested). The formula for calculating these emissions would be:

EQUATION 7

Emissions from SO_2 Scrubbing (Gg C) = Total Coal Consumption (10^3 t)
x Fraction burned in plants equipped with scrubbers(%)
x Average Sulphur Content of Coal in these plants (%)
x Sulphur Removal Efficiency (default value is 90%)
x 12/32 (i.e., the Carbon/Sulphur Ratio)

Finally, to convert from carbon emissions (in Gg) into CO_2 emissions (in Gg), it is necessary to multiply by 44/12, the molecular weight ratio of CO_2 to C.

1.9 Fugitive Emissions From Oil And Natural Gas Activities

1.9.1 Overview

This section covers fugitive emissions of greenhouse gases (GHGs) from oil and natural gas activities. The category includes all emissions from the production, processing, transport and use of oil and natural gas, and from non-productive combustion It excludes use of oil and gas or derived fuel products to provide energy for internal use, in energy production processing and transport. The latter are considered fuel combustion and treated in an earlier section of this chapter. Fugitive emissions do include, however, emissions which result from the combustion of natural gas during flaring operations.

By far the most important components of this subcategory are methane emissions from oil and gas production, and from all aspects of natural gas activities. The majority of this section identifies and describes different methane emission sources from oil and natural gas, and presents a default methodology to estimate these emissions on a national level. The basis for estimating methane emissions from oil and gas is, however, weak for most regions at this time. Only a few detailed studies of emissions rates have been performed. Better emissions data that take into account region- and country-specific factors are needed. Information currently available indicates that gas production and transmission in the former USSR and Eastern Europe are by far the most important sources, accounting for perhaps 50 per cent of global CH_4 emissions from oil and natural gas. Because the data are so limited at present, global and regional estimates of CH_4 emissions from this source category should be considered highly uncertain.

No original work has been done within the IPCC/OECD programme on CO_2, NO_x, and NMVOC emissions from oil and natural gas. This is consistent with the programme's priorities for the first phase Considerable information has been obtained in other national and international emissions inventory programmes for NMVOCs because of the importance of these gases for local and regional (as well as global) pollution. References to some of the available sources of emission factor data and other information for calculating emissions from this category are provided in the last subsection of this section.

1.9.2 Fugitive Emissions of Methane

Background

Fugitive emissions of methane from oil and gas activities probably account for about 30 to 60 Tg per year of global methane emissions. Sources of fugitive emissions within oil and gas systems include releases during normal operation, such as emissions associated with venting and flaring, chronic leaks or discharges from process vents, emissions during maintenance, and emissions during system upsets and accidents.

Oil and Natural Gas Activities Overview:

Oil and gas activities are divided into three main parts, for this discussion

1 **Oil and Gas Production** Oil and gas are withdrawn from underground formations using on-shore and off-shore wells and are often taken simultaneously from the same geological formation, and then separated. Gathering lines are generally used to bring

the crude oil and raw gas streams to one or more collection point(s) within a production field. Because methane is the major component of natural gas, leaks or venting from these systems result in methane emissions. Oil and/or gas are produced in approximately 186 countries world-wide.

2 **Crude Oil Transportation and Refining**: Crude oil is transported by pipelines and tankers to refineries where it is stored in tanks for a period of time. Methane is present, in varying degrees, in crude oil, and leaks or venting of vapours during transport and storage result in methane emissions, particularly from crude oil tankering.

Refineries process crude oil into a variety of hydrocarbon products such as gasoline and kerosene. During the refining process, dissolved gases are separated some of which may be leaked or vented during processing. Refinery outputs, referred to as "refined products," generally contain negligible amounts of methane. Consequently, methane emissions are not estimated for transporting and distributing refined products. Refineries are operated in 102 countries.

3 **Natural Gas Processing, Transportation, and Distribution**: Natural gas is processed to recover heavier hydrocarbons, such as ethane, propane and butane, and to prepare the "dried" gas for transport to consumers. Most gas is transported through transmission and distribution pipelines. A small amount of gas is shipped by tanker as liquefied natural gas (LNG). Because only a small portion of gas is transported as LNG, emissions from LNG facilities are not included in default emission methods.

The following are the main processing, transportation, and distribution activities:

- Gas processing plant: Natural gas is usually processed in gas plants to produce products with specific characteristics. Depending on the composition of the unprocessed gas, a variety of processes may be used to remove most of the heavier hydrocarbons, or condensate, from the gas. The processed, marketable, gas is then injected into the natural gas transmission system and the heavier hydrocarbons are marketed separately. Unintentional leaks of methane occur during natural gas processing.
- Transmission pipelines: Transmission facilities are high pressure lines that transport gas from production fields, processing plants, storage facilities, and other sources of supply over long distances to distribution centres, or large volume customers. Although transmission lines are usually buried, a variety of above-ground facilities support the overall system including metering stations, maintenance facilities, and compressor stations located along the pipeline routes. These activities use gas from the pipeline as fuel and may emit methane.
- Distribution systems: Distribution pipelines are extensive networks of generally small diameter, low pressure pipelines. Gas enters distribution networks from transmission systems at "gate stations" where the pressure is reduced for distribution within cities or towns. As with transmission pipelines emissions from leaks or supporting facilities may take place.

Sources of Methane Emissions from Oil and Natural Gas Activities:

Emissions from oil and gas activities can be categorised into: (1) emissions during normal operations; (2) maintenance; and (3) system upsets and accidents. Typically the majority of emissions are from normal operations.

1 **Normal Operations:** . Emissions from normal operations can be divided into two main source categories: (1) venting and flaring and (2) discharges from process vents, chronic leaks, etc.

Venting and Flaring - Venting and flaring refers to the disposal of gas that cannot be contained or otherwise handled. Such venting and flaring activities are associated with combined oil and gas production and take place in production areas where gas pipeline infrastructure is incomplete and the natural gas is not injected into reservoirs (emissions from process vents are not included here - see next subsection).

Venting activities release methane because the vented gas typically has a high methane content. If the excess gas is burned in flares the emissions of methane will depend on how efficient the burning processes are. Generally the combustion efficiency for flare sources are assumed to be between 95 and 100 per cent. However a new study based upon measurements carried out by Norwegian Oil Industry Association - OLF (forthcoming) indicates very small amounts of unburned methane from flares, less than 0.1 per cent of the gas flared. To estimate the methane emissions from venting and flaring activities satisfactorily it is required to know the flare efficiency rates and the division between the quantity of gas vented and gas flared.

The *combined* quantity of gas vented and flared is reported by countries that produce oil and gas (Barns et al., 1990). A few countries also are able to report separately gas vented and gas flared. The reliability of the data is questionable in many cases because vented and flared amounts are not normally metered but inferred from the difference between total production and disposals.

Discharges from Process Vents, Chronic Leaks etc. - These include:

- Emissions from pneumatic devices (gas-operated controls such as valves and actuators) depend on the size, type, age of the devices, the frequency of their operation and the quality of their maintenance
- Leaks from system components are unintentional and usually continuous releases resulting from the failure of a seal or the development of a flaw, crack or hole in a component designed to contain or convey oil or gas. Connections, valves, flanges, instruments, and compressor shafts can develop leaks from flawed or worn seals, while pipelines and storage tanks can develop leaks from cracks or from corrosion.
- Emissions from process vents, such as vents on glycol dehydrators and vents on crude oil tankers and storage tanks resulting from normal operation of the facilities. However such process vents are minor methane sources in most gas production facilities
- Emissions from starting and stopping reciprocating engines and turbines.
- Emissions during drilling activities, e.g., gas migration from reservoirs through wells.

2 **Maintenance:** Includes regular and periodic activities performed in the operation of the facility. These activities may be conducted frequently, such as launching and receiving scrapers ("pigs") in a pipeline, or infrequently, such as evacuation of pipes ("blowdown") for periodic testing. In each case, the required procedures release gas from the affected equipment. Releases also occur during maintenance of wells ("well workovers") and during replacement or maintenance of fittings.

3 **System Upsets and Accidents:** System upsets are unplanned events in the system, the most common of which is a sudden pressure surge resulting from the

failure of a pressure regulator. The potential for unplanned pressure surges is considered during facility design, and facilities are provided with pressure relief systems to protect the equipment from damage due to the increased pressure. Relief systems vary in design. In some cases, gases released through relief valves may be collected and transported to a flare for combustion or re-compressed and re-injected into the system. In these cases, methane emissions associated with pressure relief events will be small. In older facilities, relief systems may vent gases directly into the atmosphere or may send gases to flare systems where complete combustion may not be achieved.

The frequency of system upsets varies with the facility design and operating practices. In particular, facilities operating well below capacity are less likely to experience system upsets and resulting emissions. Emissions associated with accidents are also included under the category of upsets. Occasionally, gas transmission and distribution pipelines are accidentally ruptured by construction equipment or other activities.

Table 1-45 lists the most important sources of emissions within each segment of the oil and gas industry. Based on available information, the sources listed as "major" account for the majority of emissions from each segment. Because data are limited and, because there is considerable diversity among oil and gas systems throughout the world, other possible sources are listed which may, in some cases, be important contributors to emissions.

Available Emissions Data:

Only very limited data are available that describe methane emissions from natural gas and oil activities. Estimating the types of emissions defined above is complicated by the fact that emissions rates from similar activities in various regions and countries are influenced by differences in the industry's supporting infrastructure, operating and maintenance practices, and level of technology used. Because natural gas and oil activities are complex, it is not easy to define simple relationships between emissions and gross descriptors of the activities undertaken.

TABLE 1-45
METHANE EMISSIONS FROM OIL AND NATURAL GAS ACTIVITIES

Segment	Major Emission Sources	Other Possible Emission Sources
Oil and Gas Production Oil and Gas Wells Gathering lines Treatment facilities	Venting Normal operations: fugitive emissions; deliberate releases from pneumatic devices and process vents	Flaring, maintenance, system upsets and accidents
Crude oil transportation and Refining Pipelines Tankers Storage tanks Refineries	Normal operations: fugitive emissions; deliberate releases from process vents at refineries, during loading and unloading of tankers and storage tanks	Flaring, maintenance, system upsets and accidents
Natural Gas Processing, Transportation, and Distribution Gas Plants Underground storage reservoirs Transmission Pipelines Distribution Pipelines	Normal operations fugitive emissions; deliberate releases from pneumatic devices and process vents	Flaring, maintenance, system upsets and accidents

The available published data were reviewed to identify emissions estimates that include: a detailed consideration of the physical attributes of oil and gas systems; the operation and maintenance characteristics of key facilities; and country- or region-specific factors that may influence emission rates. The following data were identified:

- **Surveys:** Several studies have surveyed system operators to estimate emissions as a fraction of production or throughput. These studies include Alphatania (1989), AGA (1989), and INGAA (1989). While these studies provide a basis for identifying the activities that operators believe are likely to be major sources of emissions, they are not based on detailed assessments of emission rates and therefore do not provide a quantitative basis for making estimates of methane emissions from oil and natural gas activities.
- **Estimates Based on "Reported Unaccounted For Gas":** Several studies, such as Hitchcock and Wechsler (1972), Abrahamson (1989) and Cicerone and Oremland (1988), have assumed that emissions can be approximated by reported amounts of "unaccounted for" gas. Unaccounted for gas is defined as the difference between gas production and gas consumption on an annual basis. Like estimates of venting and flaring, unaccounted for gas often is used as an accounting convenience to balance company or national production and consumption estimates.

  The use of unaccounted for gas estimates as estimates of emissions is questionable because factors other than emissions account for the majority of the gas listed as unaccounted for. These include: meter inaccuracies, use of gas within the system itself, theft of gas (PG&E, 1990), variations in temperature and pressure and differences in billing cycles and accounting procedures between companies receiving and delivering the gas (INGAA, 1989). Furthermore, because known releases of gas are not reflected in unaccounted for gas estimates, such as emissions from compressor exhaust, the unaccounted for gas estimates cannot unambiguously be considered an upper or lower bound on emissions.

Engineering Studies and Measurements: A small number of studies are based on detailed engineering and/or field measurement analyses. Several engineering analyses have considered the manner in which actual or model facilities are built and operated, and extrapolate facility emissions to a system-wide basis. Several measurement studies have measured emissions from operating facilities or identified actual leaks and extrapolated these measurements to estimate system-wide emissions. In general, data from engineering studies and measurements are the preferred basis for emission estimates. However, only a few of these types of studies have been performed, thereby limiting the ability to estimate emissions nationally, regionally and globally from oil and gas systems. Table 1-46 lists the studies identified and the information they contain. The methane emissions estimates from the studies in the table have been converted to common units of kilograms of emissions per petajoule of energy (kg/PJ). A total of five studies are listed, with emissions estimates for parts of North America (US EPA, 1992), Eastern Europe (Rabchuk et al., 1991), and Western Europe (Schneider-Fresenius et al., 1989, Norwegian SPCA, 1992 and Norwegian Oil Industry Association, 1993). Additionally, Barns and Edmonds (1990) present estimates based on a global assessment. Further studies are needed to improve the basis for making emissions estimates.

TABLE 1-46
SUMMARY OF METHANE EMISSION FACTORS

Data source	Study methodology	Emission factors	Applicability
US EPA (1992) All emissions have been scaled down to 1988 energy consumption or production levels	Compilation of estimates from: • detailed engineering analyses • field measurement studies	**Oil and Gas Production:**	
		290 - 4,670 kg/PJ of oil produced	Emissions from non-gas producing oil wells including fugitive emissions and maintenance emissions in the US
		39,590 - 104,220 kg/PJ of gas produced	Emissions from gas production, including fugitive emissions, dehydrator venting, bleeding from pneumatic devices maintenance, and systems upsets in the US
		2,870 - 13,920 kg/PJ of total oil and gas produced	Venting and flaring emissions from oil and gas production and fugitive emissions from gas-producing oil wells in the US
		Crude Oil Transportation and Refining:	
		110 - 1,666 kg/PJ of oil refined	Emissions from oil refining and related oil storage tanks in the US
		Natural Gas Processing, Transmission and Distribution:	
		59,560 - 116,610 kg/PJ of gas consumed	Emissions from gas processing, transmission and distribution including fugitive emissions, dehydrator venting, bleeding from pneumatic devices, maintenance, and system upsets in the US
Rabchuk et al (1991)	Compilation of estimates from •previous measurement studies •official data for 1989	**Oil and Gas Production:**	
		218 000 - 567 600 kg PJ of gas produced	Emissions from leakages at gas wells including routine equipment venting in the former USSR
		Natural Gas Processing, Transmission and Distribution:	
		340 000 - 715 800 kg PJ of gas consumed	Emissions from leakages at underground storage facilities, compressor stations, linear part of main pipelines and distribution networks in the former USSR
Schneider-Fresenius et al (1989)	Compilation of results from • Batelle study's 1988 literature survey	**Oil and Gas Production:**	
		14,800 270,00 kg PJ of gas produced	Emissions from gas production and treatment facilities in Germany
		Natural Gas Processing, Transmission and Distribution:	
		58,000 111,000 kg PJ of gas consumed	Emissions from transportation, distribution and storage of gas in Germany

TABLE 1-46 (CONTINUED)
SUMMARY OF METHANE EMISSION FACTORS

Data source	Study Methodology	Emission Factors	Applicability
Barns and Edmonds (1990)	Compilation of: •official reports and projections on international emissions	**Oil and Gas Production:**	
		96,000 kg/PJ of natural gas production	Emissions from gas production and separation facilities in the world
		6,300 - 1,019,000 kg/PJ of gas production	Emissions from venting and flaring activity by region of the world
Norwegian SPCA (1992)	Summary of: emissions estimates for 1989 based on information and measurements collected from oil companies and industry associations	**Oil and Gas Production:**	
		12,800 kg/PJ of gas produced	Emissions from cold vents and fugitive emissions
		3,200 kg/PJ of gas produced	Flare and gas turbines
		200 kg/PJ of gas produced	Pre-production emissions (well testing)
		Crude oil transportation:	
		2,500 kg/PJ oil tankered	Emissions from offshore loading of crude oil
		Natural gas processing:	
		1,800 kg/PJ of gas processed	Emissions from one Norwegian gas processing terminal
Norwegian Oil Industry Association (OLF), 1993	Summary of emission estimates based on information and measurements collected from oil associations	**Oil and Gas Production:**	
		3,000 - 7,500 kg/PJ of gas produced	Emissions from cold vents and fugitive emissions
		100 - 400 kg/PJ of gas produced	Pre-production emissions

1.9.3 Methodology For Estimating Emissions

A three-tiered approach is presented for estimating methane emissions from oil and gas activities. The specific tiers are listed below in the order of increasing sophistication, data requirements, and accuracy:

- Tier 1 - Production-Based Average Emission Factors Approach,
- Tier 2 - Mass Balance Approach, and
- Tier 3 - Rigorous Source-Specific Approach.

Countries should select the approach or combination of approaches that is most suited to their circumstances. Some important considerations may include the relative contribution of oil and natural gas to total methane emissions for the country, the available information and resources, and the complexity of the local oil and gas industry.

Regardless of the method that is used, the results must be aggregated back to a Tier 1 format to provide a consistent basis for comparison.

Note that methane emissions from combustion plant and incomplete combustion in flaring processes in the non-oil and gas industry are excluded. They are accounted for separately in the section on methane emissions from combustion and industry.

Tier 1 - Production-Based Average Emission Factors Approach

This is the simplest approach for estimating CH_4 emission from oil and gas activities, and is the only one that does not require any direct interaction with the oil and gas industry and associated regulatory agencies. Accordingly, it is the least reliable of the methods.

The required activity data may be easily referenced from published documents of the IEA or the United Nations Statistical Division, and the necessary emission factors are provided in this document. The Tier 1 Approach can be used as a starting point for any country, and may be all that is needed where the emissions from a country's oil and gas industry are comparatively small and/or where data or resources are not available to pursue a more rigorous approach.

Production Base: To estimate emissions, the following steps are recommended as a default estimation procedure:

1. Global oil and gas systems have been divided into regions with relatively homogeneous oil and gas system characteristics. Each country should decide which system characterisation best fits its own oil and gas system(s).
2. For each region, representative emission factors for each activity within each segment have been selected with the objective of taking into account the various system designs and operating practices found in each region.
3. For each country, country-specific activity levels must be obtained and multiplied by the appropriate emission factor. Emission factors for countries should be selected from those corresponding to the appropriate region.

As more data become available for oil and gas producing activities within different countries, the default methodology described above (including activity data and emission factors) should be refined. Each step is discussed below in more detail.

Regional Definitions: Regions have been defined considering the limitations in data on emission factors and activity levels, but also recognising the key differences in oil and gas systems that are found globally. The following five regions are recommended at this time

- **US and Canada:** The United States is a large producer and importer of oil and is a large producer of gas. Detailed emissions estimates are available for the United States.
- **Former USSR and Eastern Europe:** Indications are that emission rates from this region are much higher than emissions rates from other regions, in particular for the gas system. This region includes the former USSR (which is by far the largest oil and gas producer in the region), Albania, Bulgaria, Czech & Slovak Republics, Hungary, Poland, Romania, and the former Yugoslavia.
- **Western Europe:** This region is a net importer of oil and gas, and mainly produces oil and gas off shore. This region includes: Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom
- **Other Oil Exporting Countries:** This region includes the world's other major oil producing countries, the 13 OPEC members (Algeria, Gabon, Libya, Nigeria, Ecuador, Venezuela, Indonesia, Iran, Iraq, Kuwait, Qatar, Saudi Arabia and the United Arab Emirates) and Mexico. Generally, these countries produce large quantities of oil and have limited markets for gas
- **Rest of the World:** This region includes the remaining countries of Asia, Africa, Middle East, Oceania and Latin America.

In defining these regions, countries with relatively similar oil and gas systems were aggregated. Additional investigation would likely improve the definition of the regions.

Emission Factors: As discussed above, the basis for selecting emission factors is weak because very few detailed studies of emissions have been performed. Using the information summarised in Table 1-46, emission factors should be selected by industry segment and emission type for each of the regions. In some cases data from the United States were used when region-specific information was not available.

Tables 1-48 through 1-53 offer emission factors for each region. Emission factors from US EPA (1992) were used for the United States. Key emission factors for Eastern Europe and the Former USSR were taken from Rabchuk et al. and Barns et al.. Estimates were used for emission factors for venting and flaring for the several regions, including Eastern Europe.

Studies by Schneider-Fresenius et al. (1989) and Norwegian SPCA (1992) were adopted as representative of emission factors for Western European gas production, venting and flaring. No region-specific data were available for the Other Oil Exporting countries and the Rest of the World. Emission factors in these regions are expected to fall between the relatively low rates found in North America and Western Europe and the relatively high rates found in Eastern Europe. Consequently, a range of emission factors is suggested for these regions unless more information can be obtained.

Activity Levels: Data on the quantity of oil and gas produced, refined, and consumed can be obtained from the IEA or the UN Statistical Division. Sources are described in the introduction to this chapter. Data on oil refining capacity can be used to approximate oil refined. Data on oil tankered were not available by region. It is important for national experts to ensure that production figures used in calculation of apparent consumption for CO_2 emissions estimates (described in section 1.4.2 of this Chapter) are consistent with those used in this section.

Tier 2 - Mass Balance Approach

The Mass Balance Approach is only recommended for oil system releases of CH_4, and should not be used for releases from natural gas activities. No Tier 2 method exists for natural gas activities. This is a priority for future work. The Mass Balance Approach employs standard, generally easy-to-obtain, oil and gas data (i.e., production volumes, gas-to-oil ratios (GORs), and gas compositions) to estimate the maximum amount of methane that could be emitted to the atmosphere by different sectors of the oil and gas industry. These amounts are then scaled to reflect actual emissions by applying appropriate emission factors. The minimum emission factors account for the amount of gas that is disposed of by control devices, consumed by combustion equipment, conserved, or reinjected. Leak emission factors account for the amounts lost through leaks from these control/utilisation systems.

The basic procedures for performing the mass balance calculations for each oil and gas activity are set out below. Total CH_4 emissions is the sum of emissions for each of these activities. Default data and factors are provided where possible.

Oil Production: Emissions from oil production may be estimated using the relation.

$$E_{Oil\text{-}P} = Q_{Oil\text{-}P} \times GOR \times Y_{CH_4} \times K_{Oil\text{-}P} \times D_{GOR} \times 10^{12}$$

where

E_{Oil-P} = methane emissions from oil production (Tg/year)

Q_{Oil-P} = oil produced (m^3/year)

GOR = gas to oil ratio; defines the amount of gas produced (in volume) per unit of oil produced (in volume). (m^3/m^3, or dimensionless).

Y_{CH4} = methane Fraction; the volume of gas dissolved in the oil that is methane, on a volume basis, for example, 0.1 m^3 of methane per 1.0 m^3 of gas. (may be considered dimensionless)

K_{Oil-P} = emission factor for oil production, see below (dimensionless)

D_{GOR} = density of methane at the temperature and pressure at which the GOR is estimated, (g/m^3). The relevant temperature and pressure may vary, depending on the values used to calculate the GOR. For example, at 0°C and a pressure of 1 atmosphere, the density of methane is 715.4 g/m^3, and at 20°C, and a pressure of 1 atmosphere, the density of methane is 666.6 g/m^3.

The first two terms (Q_{Oil-P}, and GOR) estimate the total amount of gas that is withdrawn from the ground while the oil is produced. The term Y_{CH4} converts the total gas quantity into the quantity of methane (still on a volume basis). The emission factor (K_{Oil-P}) is the fraction of the total gas withdrawn that is emitted. At most, $K_{Oil-P} = 1$. To put the emissions estimate on a mass basis, D_{GOR} is used to estimate grams, and the conversion to teragrams follows.

The values of the emission factors are determined using the equations presented below.

$$K_{Oil-P_{min}} = 1 - \frac{Q_{Gas-fuel} + Q_{Gas-inj} + Q_{Gas-flared} + Q_{Gas-other}}{Q_{Oil-P} \times GOR}$$

where,

$K_{Oil-P_{min}}$ = minimum emission factor for oil production (dimensionless)

Q_{Oil-P} = oil produced (m^3/year)

GOR = gas to oil ratio (dimensionless)

$Q_{Gas-fuel}$ = quantity of gas used as fuel (m^3/year)

$Q_{Gas-flared}$ = quantity of gas flared (m^3/year)

$Q_{Gas-inj}$ = quantity of gas injected back into ground (m^3/year)

$Q_{Gas-other}$ = quantity of gas accounted for in some other manner and that is not emitted (m^3/year)

The minimum emission is the amount of gas not otherwise accounted for. If no gas is used as fuel, flared, injected, or otherwise handled, then the minimum emission factor is 1, (i.e., all the gas withdrawn from the ground in conjunction with the oil is emitted). If some amount of gas is accounted for, then the minimum emission factor is 1 minus the portion accounted for.

Emissions also occur due to leaks. The leak emissions are the amount of gas leaked during various types of handling. If no gas is used as fuel, flared, injected, or otherwise handled, then the leaks are zero. If some amount of gas is managed in these ways, then the leak emission is the amount of gas handled times the leak rate, which is expressed as a fraction. The following is the equation for the leak emission factor:

$$K_{Oil-P_{leak}} = \frac{(Q_{Gas-fuel} \times L_{fuel}) + (Q_{Gas-inj} \times L_{inj}) + (Q_{Gas-flared} \times L_{flared}) + (Q_{gas-other} \times L_{other})}{Q_{Oil-P} \times GOR}$$

$K_{Oil-P_{leak}}$ = emission factor for leaks in the systems used to handle gas during oil production

Q_{Oil-P} = oil produced (m^3/year)

GOR = gas to oil ratio; defines the amount of gas produced (in volume) per unit of oil produced (in volume) (dimensionless)

$Q_{Gas-fuel}$ = quantity of gas used as fuel (m^3/year)

$Q_{Gas-flared}$ = quantity of gas flared (m^3/year)

Q_{gas} = quantity of gas injected back into ground (m^3/year)

$Q_{Gas-other}$ = quantity of gas accounted for in some other manner (m^3/year)

L_x = leak rates for the handling of the gas in the various ways, expressed as a fraction (e.g., 0.01) (dimensionless)

The total emission factor for oil production is then estimated as:

$$K_{Oil-P} = K_{Oil-P_{main}} + K_{Oil-P_{leak}}$$

If none of the gas is controlled or utilised (i.e., $L_x = 1$ for all x), then the emission factor (K_{Oil-P}) is equal to one. This situation occurs when it is not economical to conserve or reinject the gas (e.g., there is no local market for the gas and the volumes are relatively small) and when venting of the gas is preferable to disposal by flaring. It is not then necessary to evaluate the different paths by which CH_4 emissions may occur (e.g., fugitive equipment leaks, process venting, system upsets, etc.) in these cases since the end effect is the same: essentially all the CH_4 produced is emitted to the atmosphere.

Crude Oil Transportation and Refining: The crude oil from production facilities will initially contain a certain amount of gas in solution. This gas, particularly the CH_4 fraction, evaporates quickly as this oil progresses through the storage and transportation systems en route to the refinery. When the oil reaches the refinery, it is usually fully weathered and essentially free of any CH_4.

Accordingly, the basic mass balance relation for oil transportation and refining activities may be expressed as follows:

$$E_{Oil-T} = Q_{Oil-T} \times F \times Y_{F\ CH_4} \times D_F \times 10^{-12}$$

where,

E_{C} = methane emissions from crude oil transportation and refining (Tg/year)

Q_{O} = oil transported and refined (m^3/year)

F = factor defining the amount of gas in solution with the crude oil (per unit of oil by volume). (Dimensionless)

Y_{F-CH_4} = methane fraction; the fraction of the gas in solution in the oil that is methane, on a volume basis, for example, 0.1m^3 of methane per 1.0 m^3 of gas. (Dimensionless)

K_{Oil-T} = emission factor for oil transportation and refining, see below. (Dimensionless).

D_F = density of methane at the temperature and pressure at which F is estimated. (g/m^3). The relevant temperature and pressure may vary, depending on the values used to calculate F. For example, at 0°C and at a pressure of 1 atmosphere, the density of methane is 715.4 g/m^3, and at 20°C and 1 atmosphere, the density of methane is 666.6 g/m^3.

The first two terms (Q_{O} and F) estimate the total amount of gas that is in solution with the crude oil. The term Y_{F-CH_4} converts the total gas quantity into the quantity of methane (still on a volume basis). The emission factor (K_{O}) is the fraction of the total gas in solution that is emitted (at most, K_{O} = 1). To put the emissions estimate on a mass basis, D_F is used to estimate grams, and the conversion to teragrams follows.

The value of the solution gas factor and the corresponding mole fraction of methane is determined by the type of crude oil (light, medium, heavy, or crude bitumen), the composition of the associated gas, and the initial vapour pressure of the crude oil when it is placed in the storage tanks or compartments at the production site. Typically, the initial vapour pressure will be equal to the operating pressure of the first vessel upstream of the storage facilities

Table 1-47 presents some estimated values for these two parameters at onshore and offshore facilities Better estimates may be determined by performing site specific process simulations.

TABLE 1-47
SOLUTION GAS FACTORS AND CORRESPONDING CH_4 MOLE FRACTIONS FOR DIFFERENT TYPES OF CRUDE OIL PRODUCTION AT ONSHORE AND OFFSHORE FACILITIES

Type of Crude Oil	Onshore and Offshore Facilities	
	F SOLUTION GAS FACTOR	Y_{F-CH4} MOLE FRACTION
Light	3 3 to 5 0	0 5642
Medium	3 2 to 5 0	0 1001
Heavy (Primary)	1 0	0 8723
Heavy (Thermal)	8 3	0 6666

The value of the system adjustment factor is determined using the equation below:

$$K_{Oil-T} = 1 - \frac{Q_{Collected\ CH_4}}{Q_{Oil-T} \times F \times Y_{F-CH_4}}$$

$Q_{Collected\ CH_4}$ = the amount of methane collected, and not emitted, during transportation and refining.

Often this amount is zero

Other terms defined above.

In the absence of any data regarding the volume of CH_4 collected, the value of system adjustment factor should be set to a default value of one.

Exploration and Drilling Losses

Total CH_4 emissions from the exploration and drilling sector will usually be small compared to the amount emitted by other sectors of the oil and gas industry. Consequently, a simple Tier 1 approach is perhaps most appropriate for use here.

The basic relation is shown below.

$$E_D = N_{wells} \cdot F_D$$

where,

E_D = total CH_4 emissions (Tg) from drilling and testing of oil and gas wells.

N_{wells} = number of wells drilled and tested, and

F_D = average amount of CH_4 emitted per well (Tg/well).

Tier 3 - Rigorous Source-Specific Evaluations Approach

Rigorous source-specific evaluations will generally involve compiling the following types of information and may require significant interaction with industry and associated regulatory agencies:

- detailed inventories of the amount and types of process infrastructure (e.g., wells, minor field installations, a major production and processing facilities).
- production disposition analyses (e.g., oil and gas production; vented, flared and reinjected volumes of gas; and fuel gas consumption).
- accidental releases (i.e., well blow-outs and pipeline ruptures).
- typical design and operating practices and their impact on the overall level of emission control.

The amount of emissions is then assessed by applying appropriate emission factors, empirical correlations, process simulation results, and field measurements to these data.

Some examples of detailed emission inventories that have been developed in this manner are listed below:

- US Environmental Protection Agency (US EPA). Anthropogenic Methane Emissions in the United States. Estimates for 1990: Report to the Congress. October 1992.

- * Picard, D.J., B.D. Ross, and D.W.H. Koon. A Detailed Inventory of CH_4 and VOC Emissions from Upstream Oil and Gas Operations in Alberta. Clearstone Engineering Ltd., for the Canadian Petroleum Association, March 1992.
- UK Offshore Operators Association Ltd. Methane Emissions From Offshore Oil & Gas Exploration & Production Activities. Submitted to The Watt Committee on Energy. 1993.
- Norwegian Oil Industry Association - OLF. Report from OLF Environmental Programme - Phase 2. 1993.

1.9.4 Uncertainty

Some of these studies do analyse uncertainties, but emissions estimates in general are very uncertain. The overall magnitude of the emissions estimates that will be obtained for some countries using the methods and assumptions outlined in this chapter is driven by two key studies:

- **Rabchuk et al.** report that emissions from gas production and transportation in the former USSR is very high, about 3 to 7 per cent of total gas production. Recent visits to this region indicate that system construction, maintenance, and operations may be consistent with high emissions rates (Craig, 1992). However, a better quantitative evaluation is needed to validate the current emissions estimates.
- **Barns and Edmonds** report emissions from venting and flaring by region. The emissions estimates for the OPEC countries are relatively high, and account for most of the emissions from this category. The safety concerns associated with venting, and the value of re-injecting gas into oil reservoirs to maintain reservoir pressures, would tend to render the high emissions estimates questionable. Improved data are needed to resolve this question.

The adoption of emission factor estimates from US EPA (1992) for various regions also adds uncertainty to the overall estimates US oil and gas production facilities and refineries are subject to emission control requirements. The US emission factors, particularly for refining, may under-estimate emissions in other regions. Nevertheless, this may not be a significant global uncertainty since, if the emission factors for oil production and oil refining were increased by a factor of 10 for the entire world, the estimate of total global emissions would only increase by about 1 to 6 Tg for 1988.

TABLE 1-48
US AND CANADA - EMISSION FACTORS

Emissions Type	**Emission factor** **kg/petajoule**	**Source**
Oil and Gas Production		
Oil	290 - 4.670 of Oil Production	US EPA (1992)
Gas	39.590 - 104.220 of Gas Production	US EPA (1992)
Oil & Gas	2.870 - 13.920 of Oil & Gas Production	US EPA (1992)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1.400 of Oil Refined	US EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	US EPA (1992)
Natural Gas Processing, Transport, and Distribution	59.660 - 116.610 of Gas Consumption	US EPA (1992)
Gas Processing		
Gas Pipelines		
Gas Distribution		

TABLE 1-49
EASTERN EUROPE AND FORMER USSR - EMISSION FACTORS

Emissions Type	**Emission factor** kg/petajoule	**Source**
Oil and Gas Production		
Oil	290 - 4.670 of Oil Produced	US EPA (1992)
Gas	218.000 - 567.600 of Gas Produced	Rabchuk et al. (1991)
Oil & Gas	6.300 - 29.700 of Gas Produced	Barns and Edmonds (1990)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1.400 of Oil Refined	US EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	US EPA (1992)
Natural Gas Processing, Transport, and Distribution	340.000 - 715.800 of Gas Consumption	Rabchuk et al (1991)
Gas Processing		
Gas Pipelines		
Gas Distribution		

TABLE 1-50
WESTERN EUROPE - EMISSION FACTORS

Emissions Type	**Emission factor** kg/petajoule	**Source**
Oil and Gas Production		
Oil	290 - 4,670 of Oil Produced	US EPA (1992)
Gas	14 800 - 27,000 of Gas Produced	Schneider-Fresenius et al. (1989)
Oil & Gas	13 000-16,000 of Gas Produced	Norwegian SPCA (1992)
	3,000-8,000 of Gas Produced	Norwegian O I A OLF (1993)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
	2 500 of Oil Tankered	Norwegian SPCA (1992)
Refining	90 - 1,400 of Oil Refined	US EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	US EPA (1992)
Natural Gas Processing, Transport, and Distribution	58 000 - 111,000 of Gas Consumption	Schneider-Fresenius et al. (1989)
	1,800 of Gas Processed	Norwegian SPCA (1992)
Gas Processing	-	
Gas Pipelines	-	
Gas Distribution		

TABLE 1-51
OTHER OIL EXPORTING COUNTRIES - EMISSION FACTORS

Emissions Type	**Emission factor** kg/petajoule	**Source**
Oil and Gas Production		
Oil	290 - 4,670 of Oil Produced	US EPA (1992)
Gas	39 590 - 96,000 of Gas Produced	US EPA (1992) and Barns and Edmonds (1990)
Oil & Gas	739 470 - 1,019 220 of Gas Produced	Barns and Edmonds (1990)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	US EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	US EPA (1992)
Natural Gas Processing, Transport, and Distribution	116 610 - 340,000 of Gas Consumption	US EPA (1992) and Rabchuk et al. (1991)
Gas Processing		
Gas Pipelines		
Gas Distribution		

TABLE 1-52 REST OF THE WORLD - METHANE EMISSION FACTORS		
Emissions Type	**Emission factor** kg/petajoule	**Source**
Oil and Gas Production		
Oil	290 - 4,670 of Oil Produced	US EPA (1992)
Gas	39,590 - 96,000 of Gas Produced	US EPA (1992) and Barns and Edmonds (1990)
Oil & Gas	170,000 - 209,000 of Gas Produced	Barns and Edmonds (1990)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	US EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	US EPA (1992)
Natural Gas Processing, Transport, and Distribution	116,610 - 340,00 of Gas Consumption .	US EPA (1992 and Rabchuk et al. (1991)
Gas Processing	..	..
Gas Pipelines	..	..
Gas Distribution		..

Recent Revisions to Emission Factors

The above methodology and emission factors are based on the report of an expert group convened to advise the IPCC/OECD programme on methods and data in this specific area (Ebert, et al., 1993). Since that group delivered its report in mid-1993, a more recent analysis (US EPA, in press) has provided a somewhat different interpretation of some emission factors. While this very detailed analysis endorses the basic tiered methodology included in this *Manual*, the emission factors it derives differ from those presented here. This evaluation was based on essentially the same set of measurement data as cited in this *Manual*, but draws different results from the limited available data. The results of the recent US EPA analysis are summarised in Table 1-53. The most significant differences are in natural gas processing, transportation and distribution, where a more detailed set of emission factor ranges are recommended for non-OECD countries, some which are based on production of natural gas and some which are based on consumption of natural gas (which is the case for all of the factors provided above). Where emission factors are provided for more than one subcategory, they are intended to be additive, and would result in a higher total emissions estimates. Other differences in this US EPA analysis are that venting and flaring emissions for Western Europe are based on oil rather than gas production, and there are minor revisions to some factors for fugitive and other emissions from gas production.

These differences are significant, even given the overall uncertainty in this category, and should be considered carefully by national experts in regions where emissions from this source category are significant. It is hoped that the differences can be resolved of explained in more detail in the final version of these *Guidelines*.

TABLE 1-53
REVISED REGIONAL EMISSION FACTORS FOR METHANE FROM OIL AND GAS ACTIVITIES (kg/PJ)

Source Type	Basis	Western Europe	US & Canada	Former USSR, Central & Eastern Europe	Other Oil Exporting Countries	Rest of the World
OIL & GAS PRODUCTION						
Fugitive and Other Maintenance Emissions from Oil Production	Oil Produced	300 - 5.000	300 - 5.000	300 - 5.000	300 - 5.000	300 - 5 000
Fugitive and Other Maintenance Emissions from Gas Production	Gas Produced	15.000 - 27.000	46.000 - 84.000	140.000 - 314.000	46.000 - 96.000	46.000 - 96 000
Venting & Flaring from Oil and Gas Production	Oil & Gas Produced[1]	-	3.000 - 14.000	-	-	-
	Oil Produced	1.000 - 3 000	-	-	-	-
	Gas Produced	-	-	6.000 - 30.000	758 000 - 1.046.000	175 000 - 209 000
CRUDE OIL TRANSPORTATION, STORAGE AND REFINING						
Transportation	Oil Tankered	745	745	745	745	745
Refining	Oil Refined	90 - 1.400	90 - 1.400	90 - 1.400	90 - 1.400	90 - 1.400
Storage Tanks	Oil Refined	20 - 250	20 - 250	20 - 250	20 - 250	20 - 250
NATURAL GAS PROCESSING, TRANSPORT AND DISTRIBUTION						
Emissions from Processing, Distribution and Transmission	Gas Produced	-	-	288.000 - 628.000	288.000 (high)[2]	288 000 (high)[2]
	Gas Consumed	72.000 - 133 000	57.000 - 118.000	-	118 000 (low)[3]	118 000 (low)[3]
Leakage at industrial plants and power stations	Non-residential Gas Consumed[4]	-	-	175.000 - 384.000	0 - 175.000	0 - 175 000
Leakage in the residential and commercial sectors	Residential Gas Consumed[5]	-	-	87.000 - 192.000	0 - 87.000	0 - 87 000

[1] In the US and Canada, the emissions are based on total production of both oil and gas produced

[2] The emission factor of 288.000 kg PJ of gas produced is used only for the high emissions estimate

[3] The emission factor of 118.000 kg PJ of gas consumed is used only for the low emissions estimate

[4] Gas consumption by utilities and industries

[5] Gas consumption by the residential and commercial sectors

Source US EPA (in press)

1.9.5 Fugitive Emissions Of Other GHGs

Methane is by far the most important greenhouse gas emitted on a fugitive basis from oil and gas activities However, other GHG's are clearly emitted and should be included in a comprehensive national inventory.

After methane, the most significant fugitive emissions from oil and gas activities are of non-methane volatile organic compounds (NMVOCs). Oil and gas are largely composed of organic compounds, and releases through evaporation or leakages are likely at all stages wherever the fuels or their products come into contact with the atmosphere. Fugitive emissions from refining, transport and distribution of oil products are a major component of national NMVOC emissions in many countries.

The IPCC/OECD programme has not yet addressed the indirect GHG's (including NMVOCs) in detail. This is consistent with the initial priorities within the programme - which focused on the direct greenhouse gases, CO_2, CH_4, and N_2O. However, because these gases are important contributors to a range of local and regional (as well as global) atmospheric pollution problems, they have been widely studied and reported elsewhere.

National experts interested in including the other fugitive emissions of GHG's from oil and natural gas systems should consult the existing literature which provides detailed emission factors and procedures for calculating emissions. Some key examples are:

- Default Emission Factors Handbook (EEATF, 1992);
- Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993)
- Joint Emission Inventory Guidebook (CORINAIR/EMEP, 1995 forthcoming)
- EMEP and CORINAIR Emission Factors and Species Profiles for Organic Compounds. (Veldt, 1991);
- US EPA's Compilation of Air Pollutant Emissions Factors (AP-42), 4th Edition 1985, (US EPA, 1985), and Supplement F, (US EPA, 1993);
- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987)

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2 INDUSTRIAL PROCESSES

Overview

Greenhouse gas emissions are produced from a variety of industrial activities which are not related to energy. The main emission sources are industrial production processes which chemically or physically transform materials from one state to another. During these production processes, many different greenhouse gases (CO_2, CH_4, N_2O, CO) can be released. Cement production is perhaps the most notable example of such an industrial process that releases a significant amount of CO_2.

In some instances industrial process emissions are produced in combination with energy combustion emissions. To the extent that these emissions are the direct result of the fuel combustion, they are included as energy emissions, not industrial process emissions. This will avoid double counting since these emissions should be estimated as a result of energy consumption activities (see the Energy Chapter). Also, all emissions, including evaporative emissions, which occur in energy transformation activities (e.g., petroleum refining) are discussed in the Energy Chapter. Other evaporative emissions, primarily of NMVOCs, are not included in the Industrial Processes Chapter. These sources, also referred to as "area sources" are now treated separately in the Solvent and Other Product Use Chapter. Refer to *Volume 1, Reporting Instructions* for further discussion of source category definitions and reporting issues.

At this time, cement production is the only process for which a detailed methodology is proposed for emissions estimation. However, it has been recommended that all processes generating emissions be identified, the level of emissions from these processes evaluated, and appropriate emission estimation methodologies developed. Some preliminary information is provided for CO_2, CH_4 and N_2O emissions estimation from industrial processes. Experts have suggested general additions to the range of source activities to be addressed in this *Guidelines* document. Some of these are listed in Table 2-1 of this chapter. This is not intended to be a definitive list, but rather to be a working list which will evolve over time as methods improve.

2.1.1 Chapter Organisation

The remainder of the chapter is organised by gases of concern. The next section discusses CO_2 emissions from industrial processes including cement manufacturing. The next two sections summarise available preliminary information on industrial process sources of CH_4 and N_2O respectively. The final section discusses sources of other GHGs from industrial processes. The IPCC/OECD programme has not yet addressed these gases in detail. Instead, this section identifies some of the major information sources already available from other international and national emissions inventory programs. The sections in this chapter dealing with industrial process emissions give background information on the sources and uncertainties associated with estimating emissions for the most important gases and source categories. This is consistent with the initial priorities under the IPCC/OECD programme. National experts are encouraged to report any other relevant data, along with documentation of methods and assumptions used. This will greatly assist in the development of more complete methods for future editions of the IPCC *Guidelines*.

TABLE 2-1
EMISSIONS FROM PRODUCTION PROCESSES

PROCESS	POLLUTANTS					
	NO_x	NMVOC	CH_4	CO	CO_2	N_2O
Cement Production	X				X	
Lime Manufacturing					X	
Agricultural Liming					X	
Aluminium Production	X	X	X	X	X	
Ferro-alloy Production	X	X	X	X	X	
Calcium Carbide Production				X	X	
Coke Production	X	X	X	X	X	
Nitric Acid Production	X					X
Nitrogen Fertiliser Production	X					
Adipic Acid						X
Steel Plant (electric, BOF, etc.)	X	X	X	X	X	
Ammonia Production		X	X		X	X
Sodium Carbonate					X	
Urea Production						X
Carbon Black		X				
Ethylene Production		X			X	
Propylene Production		X				
1,2 Dichlorothane Production		X				
Vinylchloride Production		X				
Polyethylene Low Density Production		X				
Polyethylene High Density Production		X				
Polyvinylchloride Production		X				
Polypropylene Production		X				
Styrene Butadiene		X				
ABS Resins		X				
Ethylene Oxide		X				
Formaldehyde Production		X				
Ethylbenzene Production		X				
Styrene Butadiene Latex		X				
Styrene Butadiene Rubber		X				
Phtalic Anhydride Production		X				
Acrylonitrile Production		X			X	
Chipboard Production		X	X		X	
Paper Pulp Production		X	X			
Bread Production		X			X	
Wine Production		X			X	
Beer Production		X			X	
Spirits Production		X			X	
Nitrate Production					X	

Greenhouse Gas Emissions From Industrial Processes

2.2.1 Cement Manufacturing

Carbon dioxide emitted during the cement production process represents the most important non-energy industrial process source of global carbon dioxide emissions. Cement production accounts for about 2.4 percent of total global industrial and energy CO_2 emissions (Marland et al., 1989). Carbon dioxide is produced during the production of clinker, an intermediate product from which cement is made. High temperatures in cement kilns chemically change raw materials into cement clinker (greyish-black pellets about the size of 12mm-diameter marbles). Specifically, calcium carbonate ($CaCO_3$) from limestone, chalk, or other calcium-rich materials is heated, forming lime (calcium oxide or CaO) and carbon dioxide in a process called calcination or calcining:

$$\boxed{CaCO_3 + \text{Heat} \rightarrow CaO + CO_2}$$

This lime combines with silica-containing materials, provided to the kiln as clays or shales, to form dicalcium or tricalcium silicates, two of the four major compounds in cement clinker (Griffin, 1987). The clinker is then removed from the kiln, cooled, and pulverised into an extremely fine grey powder. During this operation a small amount of gypsum is added to regulate the setting time of the cement. The finished product is called "Portland" cement.

It should be noted that when poured concrete is curing, some CO_2 is reabsorbed by the concrete from the atmosphere. This CO_2 reabsorption is, however, believed to be only a small fraction of the CO_2 emission resulting from cement production and is therefore usually ignored in emission calculations.

Most of the cement currently produced in the world is of Portland cement type, which contains 60 to 67 percent lime by weight. Other speciality cements are lower in lime, but are typically used in small quantities. Research is underway on cement formulations that have similar structural properties to Portland cement, but require less lime (Tresouthick and Mishulovich, 1990). Carbon dioxide emissions from cement production are essentially directly proportional to lime content, so production of cements lower in lime yield less CO_2.

Because carbon dioxide is emitted during clinker production (rather than cement production itself), emission estimates should be based on the lime content and production of *clinker*. Estimating emissions based on the lime content and production of *finished cement* ignores the consideration that some domestic cement may be made from imported clinker, or that some finished cement may use additional lime that is not accounted for in the cement calculations. Clinker statistics, however, may not be readily available in some countries. If this is the case, cement statistics can be used. The differences between the lime content and production of clinker and cement, *in most countries*, are not significant enough to affect the emission estimates.

Estimating CO_2 Emissions from Cement

Estimation of CO_2 emissions from cement production is accomplished by applying an emission factor, in tonnes of CO_2 released per tonne of clinker produced, to the annual clinker output.[1] The emission factor (EF) is the product of the fraction of lime used in the cement clinker and a constant reflecting the mass of CO_2 released per unit lime:

$$EF_{clinker} = \text{Fraction CaO} \times (44 \text{ g/mole } CO_2 / 56.08 \text{ g/mole CaO})$$

or

$$EF_{clinker} = \text{Fraction CaO} \times 0.785$$

There are two methods for calculating this emission factor. The first is to assume an average CaO fraction in clinker. Since clinker is mixed with gypsum, which contains less lime per unit, to make cement, clinker has a higher lime percentage than finished cement. The average clinker lime percentage was found to be 64.6 per cent[2]. This number was multiplied by the molecular weight ratio of CO_2/CaO (0.785) to achieve a clinker emissions factor of 0.5071 tonnes of CO_2/tonne of clinker produced.

$$EF_{clinker} = 0.646 \times 0.785 = 0.5071$$

A second method is to assemble country or regional data on clinker production by type and clinker CaO content by type, then calculate a weighted average for cement lime content in the country. In most countries, the difference in the results of these two methods is likely to be small; any error in the lime content assumption is likely to be smaller than the uncertainty in clinker and cement production figures (Griffin, 1987).

If information on clinker production is not readily available, an emissions factor in tonnes of CO_2 released per tonne of cement produced can be applied to annual cement production instead. This approach has been followed by Marland et al. (1989), who took the average CaO content of cement to be 63.5 per cent, yielding an emission factor of 0.4985 CO_2/cement (0.136 t CO_2 as C/t cement).

$$EF_{cement} = 0.635 \times 0.785 = 0.4985$$

Additional research indicates that "masonry cement", as opposed to "Portland cement" requires additional lime, over and above the lime used in its clinker. The following formula can be used to account for this activity:

$$a \times (\text{All Cement Production}) \times ((1-1/(1+b)) \times c) \times 0.785 = \text{tonnes } CO_2 \text{ from CaO added to masonry cement}$$

where:

a = fraction of all cement produced that is masonry cement (e.g. 0.1, 0.2)

b = fraction of weight added to masonry cement by non-plasticiser additives such as lime, slag, and shale (e.g. .03, .05)

c = fraction of weight of non-plasticiser additives that is lime (e.g. 0.6, 0.8) a x (All Cement Production) = masonry cement production

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[1] Note that the estimation of CO_2 from energy use during cement production is explained in the energy chapter; these emissions should be reported under Energy: Fuel Combustion activities.

[2] Gregg Marland, ORNL, Personal communication.

((1-1/(1+b)) x c) = fraction of lime in masonry cement not attributable to clinker

((1-1/(1+b)) x c) x 0.785 = an emissions factor of CO_2 from masonry cement additives

Data Sources

International cement production data are available from the United Nations (1988) and from the US Bureau of Mines (1988). In some countries, national data may be available from appropriate government ministries. There is substantial overlap between the US Bureau of Mines and the UN data sets, but the former is more complete. Published information is also available from the European Cement Association (CEMBUREAU, 1990).

Recommended Method

The recommended method for estimating CO_2 emissions from cement production is to multiply the most reliable figures available for tonnes of clinker produced by an emission factor of 0.5071 t CO_2/t clinker. Alternatively, cement production can be multiplied by an emission factor of 0.4985 t CO_2/t cement.

2.2.2 Other Industrial Processes

There are many other processes which may be significant sources of CO_2 for some countries. In the national inventories collected by the IPCC/OECD joint programme, CO_2 emissions from the following processes have been reported:

Production: coke, iron, steel,[3] aluminium, ferro-alloys, fertilisers, limestone, lime, dolomite, bricks, glass, paper, pulp, and print, soda ash and CO_2 manufacture.

Consumption: limestone and soda ash.

In estimating emissions from these sources, it is expected that most categories will use the following simple method:

Physical units of production (e.g. tonnes product)
x Emission Factor (e.g. tonnes CO_2/tonne product)
= Emissions (tonnes CO_2)

As more national data is collected and evaluated in this area, we expect to be able to develop and provide formulae and default emissions for additional categories (IPCC, 1993).

It should be noted that when industrial processes produce CO_2 emissions that are based on biomass carbon inputs (e.g., beverages, food, etc.), these should not be considered net CO_2 emissions.

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[3] When attempting to estimate CO_2 emissions from iron and steel production processes, national experts may find it useful to consult *Carbon Dioxide and the Steel Industry*, published by the International Iron and Steel Institute.

Methane Emissions From Industrial Processes

Most global methane budget estimates do not include a large and diverse group of minor industrial sources which emit methane into the atmosphere. This source class deals with non-combustion processes in industry and excludes methane emitted from fuel combustion in the production process. Individually, these sources emit minor quantities of methane, but collectively their contribution to the global budget may be significant.

Non-combustion processes include the following:

- primary metals production and associated processes (coke, sinter, pig iron, steel);
- chemical manufacturing processes; production of a variety of chemicals like carbon black, ethylene, dichloroethylene, styrene and methanol.

Table 2-2 summarises estimated global methane emissions from some specific non-combustion industrial processes. These processes include: production of iron/steel (coke included); oil refining; production of carbon black, ethylene, dichloroethylene, styrene and methanol.

Iron & steel production, appearing as the major source in this category, may be further subdivided into coke, sinter and pig iron production as sources of process emissions. The other processes that have been analysed for process emissions of methane are of minor importance due to low estimated production level and/or emission (Berdowski et al., 1993b).

TABLE 2-2
GLOBAL EMISSION FACTORS AND EMISSIONS OF METHANE FROM INDUSTRIAL MANUFACTURING PROCESSES

Manufacturing process	Production * (Tg)	Emission factor (g/kg)	Emission (Tg)	References Emission factor
Integrated iron & steel plant	750	< 3	< 2	[1-6]
of which Coke production	400	0.5	0.2	[1. 5. 6]
Sinter production	650	0.5	0.3	[3. 4. 6]
Pig iron production	550	0.9	0.5	[2]
Carbon black	5	11	0.06	[3. 7]
Ethylene	40	1	0.04	[3. 7]
Dichloroethylene	20	0.4	0.01	[3. 7]
Styrene	15	4	0.06	[3. 7]
Methanol	15	2	0.03	[3. 7]

Note

* Production data are estimated from various data sources (UN amongst others)

Source. Berdowski et al., (1993b)

[1] Schade, H. (1980)

[2] Stallings, R.L. (1984)

[3] Shareef, G.S., W.A. Butler, L.A Bravo and M B Stockton (1988)

[4] Stoehr, R.A. (1982)

[5] Project Emission registration.

[6] Barnard, W.R. (1990)

[7] Stockton, M.B. and J.H.E. Stelling (1987)

Uncertainties

Further study and clarification of the sources included in this category and their global average emission factors are required in order to arrive at final conclusions with respect to the importance of this source category in total global methane emissions. Table 2-3 presents the estimated global total methane emissions from non-combustion industrial processes along with estimated ranges. The estimated range presented in the table illustrates the uncertainty of point estimates. Wide ranges, such as those presented, imply the need for further examination of the data used, particularly for iron and steel industries and oil refineries.

Methane from industrial processes is estimated to be only 3 per cent of all CH_4 emissions from fossil fuels, and hence seems negligible on a global scale. However, it is recommended that national experts make a critical review of all possible sources in this category because their inclusion may be quite relevant in some national inventories.

N_2O Emissions From Industrial Processes

Non-combustion industrial processes resulting in N_2O emissions are recognised as important anthropogenic contributors to global nitrous oxide emissions. It is estimated that this source category represents 10 to 50 per cent of anthropogenic N_2O emissions and 3 to 20 per cent of all global emissions of N_2O (IPCC, 1992). Three sources of N_2O emissions have been identified within this category: adipic acid production, nitric acid production, and the production of other chemicals.

Adipic acid

Adipic acid is a raw material primarily used for the manufacturing of 6.6 nylon and is generally produced from cyclohexane. Cyclohexane is used to produce so-called "KA", which is subsequently oxidised with nitric acid to produce adipic acid. This oxidation step unavoidably produces nitrous oxide as a side-product with an associated emission factor (for unabated emissions) of 300 g N_2O/kg adipic acid produced (Thiemens and Trogler, 1991).

Figures for global adipic acid production are estimated to be 1.8 Tg, with associated emissions of 0.37 Tg N_2O or 0.24 Tg N_2O in units of N (-N). This emissions estimate assumes a total of 0.55 Tg of N_2O initially produced during the adipic acid production process with an average abatement of about 32 per cent (Reimer et al., 1992). The abatement of N_2O results from the treatment of the off-gases in a reductive furnace. A number of adipic acid producers treat the off-gases with the aim of reducing NO_x emissions, but the treatment also destroys nitrous oxide (Reimer et al., 1992, and McCulloch, 1993).

Nitric acid

Nitric acid (HNO_3)is a raw material used mainly as a feedstock in fertiliser production. As mentioned above, nitric acid is also a component in the production process of adipic acid. Of the 50 to 65 Tg nitric acid produced globally each year, about 1.6 Tg is used by the adipic acid industry (Reimer et al., 1992). Off-gas measurements at DuPont showed emission factors ranging from 2-9 g N_2O/kg HNO_3 or 6-26 g N_2O-N/kg HNO_3-N (Reimer et al., 1992, and McCulloch, 1993). Using this range, global N_2O emissions from nitric acid production are estimated at 0.1-0.45 Tg N_2O or 0.06-0.3 Tg N_2O-N.

Although no abatement techniques are specifically directed at removing nitrous oxide, the emission factors presented include any effect of other abatement systems that may be applied. (McCulloch, 1993) The generation of N_2O in this production process is likely to be accidental, not unavoidable. It is not known how representative either the DuPont nitric acid production process is, or the derived emission factor for N_2O for the global production of nitric acid (Olivier, 1993a).

TABLE 2-3
ESTIMATED GLOBAL METHANE EMISSIONS FROM INDUSTRIAL PROCESSES (Tg CH_4 PER YEAR)

Source category	Emission estimate	Estimate range
Industrial processes		
• Iron & steel	2	04 - 4
• Chemical manufacturing	02	01 - 2
• Miscellaneous	06	06
Total	3.3	16 - 95

Source: Berdowski et al., 1993a

Emissions calculation methodology

Estimation of N_2O emissions from adipic acid and nitric acid production requires four distinct assumptions or type of data: 1) production data on adipic acid and nitric acid, respectively; 2) default emission factors (without specific N_2O abatement); 3) applicable abatement factors for N_2O; and 4) the part of the activity level for which a specific abatement factor applies.

The recommended calculation scheme is described by the following basic formula.

$$\boxed{N_2O \text{ Emissions} = \Sigma\,(\text{Activity}_{ij} \times \text{EF}_{ij})}$$

where:

i = type of activity

j = abatement factor applicable to activities of type i and with specific abatement technology j

Activity_{i} = production level (tonne of product annually produced) for activity of type i and with abatement technology factor j

EF_{ij} = Effective Emission Factor (kg/tonne product) for activity of type i and with abatement technology factor j.

Abatement technology factor = 1 - fraction abated

Total emissions for a country is the sum across activities and sub-activities with distinct abatement levels. In the absence of information on the abatement factor one may either choose to disregard it or instead use a range for this factor. When production figures are not available, then production capacity figures of national production facilities can be used instead to estimate associated emissions (Olivier, 1993b). Table 2-4 lists the emission factors and level of abatement discussed in the adipic acid and nitric acid sections.

TABLE 2-4
ESTIMATED EMISSION FACTORS AND ABATEMENT FACTORS FOR INDUSTRIAL SOURCES OF N_2O

Activity	Emission factor ($g\ N_2O/kg$)	Emission factor range ($g\ N_2O/kg$)	Percentage abated (%)
Adipic acid production	300	-	32*
Nitric acid production	NA	2-9**	0***

* Global average value for total AA industry; global value for Du Pont: 53%; national uncertainty range not available.

** (6-26 g N_2O-N/HNO_3-N)

*** At present no specific N_2O abatement techniques are in use.

Source: (Olivier. 1993b) and references therein (Thiemens and Trogler. 1991). (McCulloch. 1993)

In general. emission abatement also needs to be considered when estimating emissions from industrial sources Technical options for reducing the N_2O emissions have been developed and Table 2-5 lists some of these. Some of the options may not be technically or economically feasible at present, but further research should improve the possibilities.

TABLE 2-5
OVERVIEW OF TECHNICAL OPTIONS FOR N_2O REDUCTION

Source	Global strength ($Tg\ N_2O$-N/yr)	Options
Industry		
1 adipic acid	0.4-0 6	Incineration (technically and economically feasible). research programme On long term. • alternative production process for adipic acid • alternatives for applications of 6.6-nylon
2. nitric acid	0.1-0.3	On long term. • alternative production process for nitric acid • alternatives for applications of 6.6-nylon • modify/optimise production processes
Source (Olivier. 1993b)		

Other chemicals production

The industrial production of other chemical compounds has been identified as a source of nitrous oxide. There has not been enough study to determine whether this represents a significant global source of N_2O. Emissions reported in the Netherlands in the chemical industry showed an emission of about 1.7 Gg N_2O in 1990 from the production of chemicals other than adipic acid or nitric acid. (Project Emission Registration, 1990).

The precise nature and location of the processes that produce these emissions are not known. Suggested sources are related to either a process using a N-compound or a catalytic reduction step. Although global N_2O emissions from this source category will probably be small as compared to emissions associated with adipic acid and nitric acid production, further investigation is recommended. It is possible that other industrial sources make significant contributions at a national level. The Netherlands reports that this source contributes about 25 per cent of the total energy related emissions of national N_2O in 1988-1990, or about 6.6 kton N_2O/yr. (Van den Born et al., 1991). The study suggests that any process in which a nitrogen compound is used or catalytic reduction is applied can be a source of N_2O emissions (Olivier, 1993a).

Emissions calculation methodology

It is recommended that national inventories include the adipic acid and nitric acid production processes at this time. Adipic acid and nitric acid manufacture should be included as source categories in national inventories. Other industrial processes can be included if the national experts have data on relevant processes. It is likely that these figures will be highly country-specific, since both process conditions and application of abatement technology of some kind may be very different for different countries.

It is recommended that further research on industrial processes focus on N_2O emissions in measurements of the off-gases and other emissions. A more comprehensive study of industrial processes and N_2O emission measurements at production sites may reveal more processes in which nitrous oxide is released. More representative measurements will further reduce the uncertainty in the current estimate of global emissions from this source category (Olivier, 1993b).

Other GHGs From Industrial Processes

Although the major GHG emissions have been dealt with above, there are other GHG emissions from industrial processes. For example, carbon tetrafluoride - CF_4 and hexafluoroethane - C_2F_6 are emitted during aluminium production, and sulphur hexafluoride - SF_6 is emitted during the production of magnesium. These may be significant sources for some countries. The following simple method can be used to estimate these GHGs:

Physical units of production	x	Emission Factor	=	Emissions
(e.g. tonnes of production)		(e.g. tonnes CO_2/ tonne product)		(e.g. tonnes CO_2)

The IPCC/OECD documents do not provide specific examples of emissions factors for other GHGs. For information on emissions factors and estimation procedures for GHGs which are currently not provided in this chapter, experts should consult extensive existing literature developed by other emissions inventory programmes. Some key examples are:

- Default Emission Factor Handbook (EEATF, 1992);
- US EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Supplement F (AP-42) (US EPA, 1993);
- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987).
- Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993).
- Joint Emission Inventory Guidebook (CORINAIR/EMEP, 1995 forthcoming).

2.2.3 Conclusion

There is not much information available on national emission factors and levels of abatement for emissions of GHG from industrial processes. This chapter describes basic methods and global mean values for emission factors for the following GHG sources:

- CO_2 from cement production;
- N_2O from adipic acid production;
- N_2O from nitric acid production.

In addition, the chapter discusses possible sources and basic approaches to estimate CO_2, CH_4, and N_2O from other industrial processes. National experts are encouraged to report any relevant emissions for which data are available, along with documentation of methods used. This will greatly assist in the development of more complete methods for future editions of IPCC *Guidelines*.

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3 SOLVENT AND OTHER PRODUCT USE

3.1 Overview

Solvents and related compounds are important for greenhouse gas (GHG) and other emission inventories because they are a significant source of emissions of non-methane volatile organic compounds (NMVOCs). No other GHGs are emitted in significant amounts from the use of solvents and related compounds, which include chemical cleaning substances used in dry cleaning, printing, metal degreasing, and a variety of industrial applications as well as household use. Also included in this category are paints, lacquers, thinners and related materials used in coatings in a variety of industrial, commercial and household applications. Table 3-1 lists some of the potentially important subcategories included under this source category.

This category also includes evaporative emissions of greenhouse gases arising from other types of product use. For example, N_2O emissions from medical use and emissions arising from the use of hydrofluorocarbons (HFCs) in applications like foam-blowing, cooling and aerosols.

All of the substances included here contain significant amounts of NMVOC. Emissions are produced through evaporation of the volatile chemicals when these products are exposed to air. Non-methane volatile organic compounds (NMVOCs) are often emitted in significant quantities from evaporation during the variety of dispersed activities discussed above. These emissions are sometimes referred to as "area" sources because they occur in large numbers of small dispersed applications, rather than from large centralised industrial processes (or "point" sources).

Solvent and other product use is treated as a separate category in detailed inventory procedures (e.g., CORINAIR) because the nature of this area source requires a somewhat different approach to emissions estimation than that used for calculating other emissions categories. The draft IPCC *Guidelines* treats the category separately for this reason.

3.2 NMVOC Emissions from Solvent and Other Product Use

NMVOC emissions estimates are characterised by high uncertainty. This is especially true for the solvent use source category on a global scale. The contribution of this source category is believed to be quite significant. A preliminary analysis estimated total global NMVOC release from solvent use to be about 11 per cent of total NMVOC emissions (Watson, et al., 1991).

Based on national GHG emissions inventories, NMVOC emissions from these sources can represent a much larger share of the total NMVOC emissions for some countries. NMVOC from solvent use represents 31 per cent of the total NMVOC emissions for both Italy and Denmark. (ENEA, 1991, Fenger et al., 1990) The Netherlands estimates solvent use to account for 25 per cent, and both Finland and the United States estimate emissions to be 24 per cent of their total NMVOC emissions (van den Born et al., 1991, Boström et al., 1992, US EPA, 1991). By contrast, emissions from solvent use in Nigeria were only 3 per cent of the total NMVOC (Obioh et al., 1992).

3.2.1 Estimating Emissions

The wide variations in national emissions from solvent and other product use highlight the differences in their use between countries and some of the difficulties associated with accurately estimating emissions from these sources.

There are two basic approaches to estimation of emissions from Solvent and Other Product Use, which depend on the availability of data on the activities producing emissions and the emission factors.

1 **Production-based** - In some cases, solvent or coating use is associated with centralised industrial production activities, such as automobile and ship production, textile manufacture, paper coating, chemical products manufacture, etc. In these cases it is generally possible to develop NMVOC emission factors based on unit of product output. These are based on the amount of paint, solvents, or other chemically volatile products consumed per unit of production of the final products. Once reasonable factors are developed it is straightforward to estimate annual emissions based on production data which are generally available on an annual basis for most countries. Industrial production data is also compiled and published by international organisations (e.g., United Nations, 1992) and these data can be used to supplement locally available data.

2 **Consumption-based** - In many applications of paints, solvents and similar products, the end uses are too small-scale, diverse, and dispersed to be tracked directly. Therefore emissions estimates are generally based on total consumption (i.e., sales) of the solvents, paints, etc. used in these applications. The assumption is that once these products are sold to end users, they are applied and emissions produced relatively rapidly. For most surface coating and general solvent use, this approach is used. Emission factors are developed based on the likely ultimate release of NMVOC to the atmosphere per unit of product consumed. These emission factors can then be applied to sales data for the specific solvent or paint products.

The IPCC/OECD joint programme has not produced any original work on estimation of NMVOCs from the use of these products. This is for two reasons. First, NMVOC is a greenhouse gas (actually a class of gases) covered under the programme, but it has been assigned a lower priority for national experts just initiating greenhouse gas inventory work. Most methods development work within the IPCC/OECD programme has focused on providing methods and default information for the first priority gases - CO_2, CH_4, and N_2O, which are direct greenhouse gases. Second, NMVOCs are among the gases already under heavy scrutiny in national and international inventory programmes because of their role as local and regional air pollutants. Hence there is a large and growing body of literature containing guidance on estimation procedures and emission factors for NMVOCs from a number of source categories, including from solvents and other products.

National experts who are already familiar with these procedures and have emissions data available or under development, should report these data to the IPCC/OECD programme, as discussed in *Volume 1: Reporting Instructions*.

Other experts needing information should consult the existing major references such as:

- Default Emission Factor Handbook (EEATF, 1992);
- US EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Supplement F (AP-42) (US EPA, 1993);
- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987).
- Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993).
- Joint Emission Inventory Guidebook (CORINAIR/EMEP, 1995 forthcoming).

3.2.2 Uncertainties

Because NMVOC emission controls vary widely throughout the world, it is important for national experts to account for the level of emission control application in their country. Also, there may be significant differences among countries regarding the processes and equipment used. These differences can affect the level of NMVOC emissions. Finally, because estimates based on consumption data provide only an approximation of the activities associated with the manufacture of all products within a particular subcategory, there is a degree of uncertainty in the estimates (Watson, et al., 1991).

TABLE 3-1
POTENTIALLY IMPORTANT SUBCATEGORIES INCLUDED UNDER SOLVENT AND OTHER PRODUCT USE

Surface coating (e.g., painting) operations	Applications of paints, lacquer, enamel and primer to cans, wood products, metal parts, buildings, etc. Use of thinning solvents
Paper coating operations	Coating operations, mixing and use of thinning solvents
Printing and Publishing	Press operations, lithography, use of thinning solvents
General Solvent Use	Vapour degreasing, dry cleaning, textile manufacture, household solvent use.
Production of Automobiles and Trucks	Surface coating, cleaning/degreasing operations
Ship building	Surface coating, cleaning/degreasing operations
Chemical Products Manufacture and Processing	Solvents are used in a variety of applications in the manufacturing of chemicals and chemical products

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4 AGRICULTURE

4.1 Overview

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of different processes. This chapter discusses four greenhouse gas-emitting activities:

- **CH_4 emissions from domestic livestock (enteric fermentation and manure management)**
  - ***CH_4 emissions from enteric fermentation in domestic livestock***
    Methane is produced in herbivores as a by-product of enteric fermentation, a digestive process by which carbohydrates are broken down by micro-organisms into simple molecules for absorption into the bloodstream. Both ruminant animals (e.g., cattle, sheep) and some non-ruminant animals (e.g., pigs, horses) produce CH_4, although ruminants are the largest source since they are able to digest cellulose, a type of carbohydrate, due to the presence of specific micro-organisms in their digestive tracts. The amount of CH_4 that is released depends on the type, age, and weight of the animal, the quality and quantity of the feed, and the energy expenditure of the animal.
  - ***CH_4 emissions from manure management***
    CH_4 is produced from the decomposition of manure under anaerobic conditions. These conditions often occur when large numbers of animals are managed in a confined area (e.g., dairy farms, beef feedlots, and swine and poultry farms), where manure is typically stored in large piles or disposed of in lagoons.
- **CH_4 emissions from rice cultivation**

  Anaerobic decomposition of organic material in flooded rice fields produces methane, which escapes to the atmosphere primarily by transport through the rice plants. The amount emitted is believed to be a function of rice species, number and duration of harvests, soil type and temperature, irrigation practices, and fertiliser use.
- **CH_4, CO, N_2O, and NO_X emissions from agricultural burning (savanna and agricultural burning)**
  - ***CH_4, CO, N_2O, and NO_X emissions from the prescribed burning of savannas***
    The burning of savannas – areas in tropical and subtropical formations with continuous grass coverage – results in the instantaneous emissions of carbon dioxide. But because the vegetation regrows between burning cycles, the carbon dioxide released into the atmosphere is reabsorbed during the next vegetation growth period. Net CO_2 emissions are therefore assumed to be zero. But savanna burning also releases gases other than CO_2, including methane, carbon monoxide, nitrous oxide and oxides of nitrogen. Unlike CO_2 emissions, these are net emissions.

- ***CH_4, CO, N_2O, and NO_X emissions from the burning of agricultural residues***
  The burning of crop residues is not thought to be a net source of carbon dioxide because the carbon released to the atmosphere is reabsorbed during the next growing season. However, this burning is a significant source of emissions of methane, carbon monoxide, nitrous oxide, and nitrogen oxides. It is important to note that some crop residues are removed from the fields and burned as a source of energy, especially in developing countries. Non-CO_2 emissions from this type of burning are dealt with in the *Energy* module of this manual. Crop residue burning must be properly allocated to these two components in order to avoid double counting.

- **N_2O, CO_2 and CH_4 emissions from agricultural soils**

  Emissions of N_2O from agricultural soils are primarily due to the microbial processes of nitrification and denitrification in the soil. Increases in the amount of nitrogen added to the soil generally result in higher N_2O emissions (Bouwman, 1990). Increases in the input of nitrogen to the soil may result from (1) atmospheric deposition, (2) commercial fertiliser, (3) animal manures and plant residues, (4) biological N fixation, and (5) soil organic matter mineralisation. Agricultural soils may also emit or remove CO_2 and/or CH_4. For example, peat compost used as a soil amendment in agriculture and gardening may result in CO_2 emissions or removals.

4.2 Methane Emission From Domestic Livestock Enteric Fermentation And Manure Management

4.2.1 Overview Of Methane Emissions From Livestock

This section covers methane emissions from enteric fermentation and the management of manure from domestic livestock. Cattle are the most important source of methane from enteric fermentation in most countries because of their high numbers, large size, and ruminant digestive system. Methane emissions from manure management are usually smaller than enteric fermentation emissions, and are principally associated with confined animal management facilities where manure is handled as a liquid. This section presents a brief overview of the key factors affecting methane emissions from these sources. The methods for estimating these emissions are then presented.[1]

Enteric Fermentation

Methane is produced during the normal digestive processes of animals. The amount of methane produced and excreted by an individual animal is dependent primarily on the following:

- **Digestive System**
  The type of digestive system has a significant influence on the rate of methane emission. *Ruminant animals* have the highest emissions because a significant amount of methane-producing fermentation occurs within the rumen. The main ruminant animals are cattle, buffalo, goats, sheep, and camels. *Pseudo-ruminant animals* (horses, mules, asses) and *monogastric animals* (swine) have relatively lower methane emissions because much less methane-producing fermentation takes place in their digestive systems.
- **Feed Intake**
  Methane is produced by the fermentation of feed within the animal's digestive system. Generally, the higher the feed intake, the higher the methane emission. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, or pregnancy).

The amount of methane emitted by a population of animals is calculated by multiplying the emission rate per animal by the number of animals. To reflect the variation in emission rates among animal types, the population of animals is divided into subgroups, and an emission rate per animal is estimated for each subgroup. Types of population subgroup are recommended in the method[2].

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[1] All GHG emissions from the burning of animal waste are estimated in section 1.7, Greenhouse Gas Emissions from Burning Traditional Biomass Fuels. CO_2 from the burning of animal waste is part of a closed cycle and is not counted as net CO_2.

[2] Countries are encouraged to carry out emissions inventory calculations at a finer level of detail if possible. Many countries have available more detailed information than was used in constructing default values here. Countries may wish to calculate emissions estimates at a finer level of detail by subcategory – further disaggregating recommended

Human management of wildlife can affect the total number of animals and therefore their emissions, though the associated emissions are believed to be small. The key issue is distinguishing those emissions resulting from human interventions from those emissions that would have occurred naturally. No methodology for estimating these emissions is presented here, though they may be estimated if national experts can fully document their approach, including all assumptions and methods. If these emissions are estimated, they should be reported in the "Other" subcategories of the Enteric Fermentation and Animal Wastes Tables (4 A & B) of *Volume 1: Reporting Instructions*.

Manure Management

Livestock manure is principally composed of organic material. When this organic material decomposes in an anaerobic environment (i.e., in the absence of oxygen), methanogenic bacteria, as part of an interrelated population of micro-organisms, produce methane.

The principal factors affecting methane emission from animal manure are the amount of manure produced and the portion of the manure that decomposes anaerobically. The amount of manure that is produced is dependent on the amount produced per animal and the number of animals. The portion of the manure that decomposes anaerobically depends on how the manure is managed. When manure is stored or treated as a liquid (e.g., in lagoons, ponds, tanks, or pits), it tends to decompose anaerobically and produce a significant quantity of methane. When manure is handled as a solid (e.g., in stacks or pits) or when it is deposited on pastures and rangelands, it tends to decompose aerobically and little or no methane is produced.

To estimate methane emission, the animal population must be divided into subgroups to reflect the varying amounts of manure produced per animal, and the manner in which the manure is handled. Population subgroups are recommended in the method.

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activity categories and subcategories – or they may choose to subdivide the categories on some other basis which they feel is appropriate to their particular national circumstances. Working at finer levels of disaggregation does not change the basic nature of the calculations. Once emissions have been calculated at whatever is determined by the national experts to be the most appropriate level of detail, results should also be aggregated up to the minimum standard level of information requested in the IPCC proposed methodology. This will allow for comparability of results among all participating countries. The data and assumptions used for finer levels of detail should also be reported to the IPCC to ensure transparency and replicability of methods. *Volume 1: Reporting Instructions* discusses these issues in more detail.

Box 1

HUMAN WASTE USED AS FERTILISER

Human waste is sometimes used as fertiliser, and can result in emissions or removals of CH_4, N_2O or CO_2. At present, no methodology can be recommended for estimating these emissions. The development of a methodology specifically for this source has been identified as an area for future work. Countries are nevertheless encouraged to estimate emissions from this source if they are able to do so. CH_4 emissions from this source can be estimated in one of at least two ways:

- Emissions from human waste used as fertiliser may be estimated in the present section by adapting the methodology for estimating emissions from livestock manure to use the data provided below. In this case, the estimate should be reported in the "Other" line in Tables 4 A & B in *Volume 1: Reporting Instructions.*

  Bhattacharya (1993) has reported these characteristics of human waste:

  Dry waste per day = 0.107 kg/head/day
  Fractional carbon content = 0.375

  And Thomas (1994, in press) reports the following values:

  Volatile solid production = 0.06 kg/head/day
  Dry matter production = 0.09 kg/head/day
  Fractional carbon content = 4.46% of dry matter

- These emissions can also be estimated using the methodology for sewage treatment in the Waste section. In this case, the emissions should then be treated as wastewater disposed of in aerobic (shallow) ponds, and should be reported in Table 6 B.

In any case, care should be taken to avoid double counting emissions from this source.

4.2.2 Inventory Method – Overview

The method for estimating methane emission from enteric fermentation and manure management requires three basic steps:

Step 1: Divide the livestock population into subgroups and characterise each subgroup. It is recommended that national experts use three year averages of activity data if available. This is to help prevent bias in the event that the base year of the inventory was an exceptional year not representative of the country's normal activity level.

Step 2: Estimate emission factors for each subgroup in terms of kilograms of methane per animal per year – separate emission factors are required for enteric fermentation and manure.

Step 3: Multiply the subgroup emission factors by the subgroup populations to estimate subgroup emission, and sum across the subgroups to estimate total emission.

These three steps can be performed at varying levels of detail and complexity. This chapter presents the following two approaches:

- **Tier 1**
  A simplified approach that relies on default emission factors drawn from previous studies. The Tier 1 approach is likely to be sufficient for most animal types in most countries.
- **Tier 2**
  A more complex approach that requires country-specific information on livestock characteristics and manure management practices. The Tier 2 approach is recommended when the data used to develop the default values do not correspond well with the country's livestock and manure management conditions. Because cattle characteristics vary significantly by country, it is recommended that countries with large cattle populations consider using the Tier 2 approach for estimating methane emissions from cattle and cattle manure. Similarly, because buffalo and swine manure management practices vary significantly by country, it is recommended that countries with large buffalo and swine populations consider using the Tier 2 approach for estimating methane emissions for manure from these animals.

Some countries for which livestock emissions are particularly important may wish to go beyond the Tier 2 method and incorporate additional country-specific information in their estimates. Although countries are encouraged to go beyond the Tier 2 approach presented below when data are available, these more complex analyses are only briefly discussed here. Table 4-1 summarises the recommended approaches for the livestock emissions included in this inventory.

TABLE 4-1

DOMESTIC LIVESTOCK INCLUDED IN THE METHODS

Livestock	Recommended Emissions Inventory Methods	
	Enteric Fermentation	Manure Management
Dairy Cattle	Tier 2[a]	Tier 2[a]
Non-Dairy Cattle	Tier 2[a]	Tier 2[a]
Buffalo	Tier 1	Tier 2[a]
Sheep	Tier 1	Tier 1
Goats	Tier 1	Tier 1
Camels	Tier 1	Tier 1
Horses	Tier 1	Tier 1
Mules and Asses	Tier 1	Tier 1
Swine	Tier 1	Tier 2[a]
Poultry	(Not Estimated)	Tier 1

[a] The Tier 2 approach is recommended for countries with large livestock populations. Implementing the Tier 2 approach for additional livestock subgroups may be desirable when the subgroup emissions are a large portion of total methane emissions for the country.

4.2.3 Inventory Method – Tier 1 Approach

This Tier 1 method is simplified so that only readily-available animal population data are needed to estimate emissions. Default emission factors are presented for each of the recommended population subgroups. Each step is discussed in turn.

TIER 1: STEP 1 – LIVESTOCK POPULATIONS

The *average annual population* of livestock is required for each of the livestock categories listed in Table 4-1. In some cases the population fluctuates during the year. For example, a census done before calving will give a much smaller number than a census done after calving. A representative average of the population is therefore needed. In the case of poultry and swine, the number of animals *produced* each year exceeds the annual average population because the animals live for less than 12 months. The population data can be obtained from the FAO Production Yearbook (FAO, 1990) or similar country-specific livestock census reports.

The dairy cattle population is estimated separately from other cattle (see Table 4-2). Dairy cattle are defined in this method as mature cows that are producing milk in commercial quantities for human consumption. This definition corresponds to the dairy cow population reported in the FAO Production Yearbook.

In some countries the dairy cattle population is comprised of two well-defined segments: high-producing "improved" breeds in commercial operations; and low-producing cows managed with traditional methods. These two segments can be combined, or can be evaluated separately by defining two dairy cattle categories. However, the dairy cattle category does not include cows kept principally to produce calves or to provide draft power. Low productivity multi-purpose cows should be considered as non-dairy cattle.

Data on the average milk production of dairy cattle is also required. These data are expressed in terms of kilograms of whole fresh milk produced per year per dairy cow, and can be obtained from the FAO Production Yearbook or similar country-specific reports. If two or more dairy cattle categories are defined, the average milk production per cow is required for each category.

Finally, the livestock populations must be described in terms of warm, temperate, or cool climates for purposes of estimating emissions from livestock manure. Data on the annual average temperature of the regions where livestock are managed should be used as follows:

- Areas with annual average temperatures less than 15°C are defined as cool.
- Areas with annual average temperatures from 15°C to 25°C inclusive are defined as temperate.
- Areas with annual average temperatures greater than 25°C are defined as warm.

For each livestock population, the fraction in each climate should be estimated. These data can be developed from country-specific climate maps and livestock census reports. To the extent possible, the temperature data should reflect the locations where the livestock are managed. If necessary, data from nearby cities can be used. Table 4-2 summarises the animal population data that must be collected in Step 1.

TABLE 4-2

ANIMAL POPULATION DATA COLLECTED IN TIER I STEP I

Livestock	Data Collected				
	Population (# head)	Milk Production (kg/head/yr)	Population By Climate (%)		
			Cool	Temperate	Warm
Dairy Cattle	Average Annual Population	Milk Production per Head	% Cool	% Temp.	% Warm
Non-Dairy Cattle	Average Annual Population	Not Applicable (NA)	% Cool	% Temp.	% Warm
Buffalo	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Sheep	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Goats	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Camels	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Horses	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Mules and Asses	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Swine	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Poultry	Average Annual Population	(NA)	% Cool	% Temp.	% Warm

Data can be obtained from the FAO Production Yearbook and country-specific livestock census reports. Climates are defined in terms of average annual temperature as follows: Cool = less than 15°C; Temperate = from 15°C to 25°C inclusive; Warm = greater than 25°C.

TIER I: STEP 2 – EMISSION FACTORS

The purpose of this step is to select emission factors that are most appropriate for the country's livestock characteristics. Default emission factors for enteric fermentation and manure management have been drawn from previous studies, and are organised by region for ease of use. The basis for the emission factors, described more fully under Tier 2, includes the following:

- *Enteric Fermentation:*
  - *Feed Intake*: Feed intake is estimated based on the energy intake required by the animal for maintenance (the basic metabolic functions needed to stay alive) and production (growth, lactation, work, and gestation). The livestock characteristics required to estimate feed intake are taken from regional and country-specific studies and include: population structure (portion of adults and young); weight; rate of weight gain; amount of work performed; portion of cows giving birth each year; and milk production per cow.

  - *Conversion of Feed Energy to Methane*: The rate at which feed energy is converted to methane is estimated based on the quality of the feed consumed – low quality feed has a slightly higher methane conversion rate. Feed quality is assessed in terms of digestibility on a regional basis.

- *Manure Management*:
  - *Manure Production*: Manure production is estimated based on feed intake and digestibility, both of which are used to develop the enteric fermentation emission factors.
  - *Methane Producing Potential*: Methane producing potential (referred to as B_o) is the maximum amount of methane that can be produced from a given quantity of manure. The methane producing potential varies by animal type and the quality of the feed consumed. Reported measurements for selected animals are used.
  - *Methane Conversion Factor (MCF)*: The MCF defines the portion of the methane producing potential (B_o) that is achieved. The MCF varies with the manner in which the manure is managed and the climate, and can theoretically range from 0 to 100 percent. Manure managed as a liquid under hot conditions promotes methane formation and emissions. These manure management conditions have high MCFs, of 65 to 90 percent. Manure managed as dry material in cold climates does not readily produce methane, and consequently has an MCF of about 1 percent. Laboratory measurements were used to estimate MCFs for the major manure management techniques.
  - *Manure Management Practices*: Regional assessments of manure management practices are used to estimate the portion of the manure that is handled with each manure management technique.

The data used to estimate the default emission factors for enteric fermentation and manure management are presented in Appendix A and Appendix B respectively, at the end of this section.

Table 4-3 shows the enteric fermentation emission factors for each of the animal types except cattle. As shown in the table, emission factors for sheep and swine vary for developed and developing countries. The differences in the emission factors are driven by differences in feed intake and feed characteristic assumptions (see Appendix A). Although point estimates are given for the emission factors, an uncertainty of about ± 20 per cent exists due to variations in animal management and feeding. Deviations from the emission factors can be larger than 20 percent under specialised feeding or management conditions.

Table 4-4 presents the enteric fermentation emission factors for cattle. A range of emission factors is shown for typical regional conditions. As shown in the table, the emission factors vary by over a factor of four on a per head basis.

While the default emission factors shown in Table 4-4 are broadly representative of the emission rates within each of the regions described, emission factors vary among countries within regions. Also, as with the emission factors shown in Table 4-3, an uncertainty of about ± 20 per cent exists due to variations in animal management and feeding. Animal size and milk production are important determinants of emission rates for dairy cows. Relatively smaller dairy cows with low levels of production are found in Asia, Africa, and the Indian subcontinent. Relatively larger dairy cows with high levels of production are found in North America and Western Europe.

TABLE 4-3
ENTERIC FERMENTATION EMISSION FACTORS

(kg per head per year)

Livestock	Developed Countries	Developing Countries
Buffalo	55	55
Sheep	8	5
Goats	5	5
Camels	46	46
Horses	18	18
Mules and Asses	10	10
Swine	1.5	1.0
Poultry	Not Estimated	Not Estimated

All estimates are ± 20 percent.

Sources: Emission factors for buffalo and camels from Gibbs and Johnson (1993). Emission factors for other livestock from Crutzen et al. (1986).

Animal size and population structure are important determinants of emission rates for non-dairy cattle. Relatively smaller non-dairy cattle are found in Asia, Africa, and the Indian subcontinent. Also, many of the non-dairy cattle in these regions are young. Non-dairy cattle in North America, Western Europe and Oceania are larger, and young cattle constitute a smaller portion of the population[3].

Select emission factors from Tables 4-3 and 4-4 by identifying the region most applicable to the country being evaluated. The data collected on the average annual milk production by dairy cows should be used to help select a dairy cow emission factor. If necessary, interpolate between dairy cow emission factors shown in the table using the data collected on average annual milk production per head.

Table 4-5 shows the default manure management emission factors for each animal type except cattle, buffalo, and swine. Separate emission factors are shown for developed and developing countries, reflecting the general differences in feed intake and feed characteristics of the animals in the two regions. These emission factors reflect the fact that virtually all the manure from these animals is managed in dry manure management systems, including pastures and ranges, drylots, and daily spreading on fields (Woodbury and Hashimoto, 1993).

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[3] For each animal category, it is important to use the average weight of the animal during the year for estimating emissions. Because the weights of mature animals may fluctuate seasonally, a representative weight should be selected that considers conditions throughout the year. For growing animals, the average weight is generally less than the final (or end) weight of the animal at the end of the year. Growth rate statistics should be used to estimate the average weight during the year for purposes of estimating emissions.

TABLE 4-4
ENTERIC FERMENTATION EMISSION FACTORS FOR CATTLE

Regional Characteristics	Cattle Type	Emission Factor (kg/head/yr)	Comments
North America: Highly productive commercialised dairy sector feeding high quality forage and grain Separate beef cow herd, primarily grazing with feed supplements seasonally. Fast-growing beef steers/heifers finished in feedlots on grain. Dairy cows are a small part of the population	Dairy	118	Average milk production of 6,700 kg/head/yr.
	Non-Dairy	47	Includes beef cows, bulls, calves, growing steers/heifers, and feedlot cattle
Western Europe: Highly productive commercialised dairy sector feeding high quality forage and grain. Dairy cows also used for beef calf production. Very small dedicated beef cow herd. Minor amount of feedlot feeding with grains.	Dairy	100	Average milk production of 4,200 kg/head/yr.
	Non-Dairy	48	Includes bulls, calves, and growing steers/heifers
Eastern Europe: Commercialised dairy sector feeding mostly forages. Separate beef cow herd, primarily grazing. Minor amount of feedlot feeding with grains	Dairy	81	Average milk production of 2,550 kg/head/yr.
	Non-Dairy	56	Includes beef cows, bulls, and young
Oceania: Commercialised dairy sector based on grazing. Separate beef cow herd, primarily grazing rangelands of widely varying quality. Growing amount of feedlot feeding with grains. Dairy cows are a small part of the population.	Dairy	68	Average milk production of 1,700 kg/head/yr.
	Non-Dairy	53	Includes beef cows, bulls, and young
Latin America: Commercialised dairy sector based on grazing. Separate beef cow herd grazing pastures and rangelands. Minor amount of feedlot feeding with grains. Growing non-dairy cattle comprise a large portion of the population.	Dairy	57	Average milk production of 800 kg/head/yr.
	Non-Dairy	49	Includes beef cows, bulls, and young
Asia: Small commercialised dairy sector Most cattle are multi-purpose, providing draft power and some milk within farming regions. Small grazing population. Cattle of all types are smaller than those found in most other regions.	Dairy	56	Average milk production of 1,650 kg/head/yr
	Non-Dairy	44	Includes multi-purpose cows, bulls, and young.
Africa and Middle East: Commercialised dairy sector based on grazing with low production per cow Most cattle are multi-purpose, providing draft power and some milk within farming regions. Some cattle graze over very large areas. Cattle of all types are smaller than those found in most other regions.	Dairy	36	Average milk production of 475 kg/head/yr.
	Non-Dairy	32	Includes multi-purpose cows, bulls, and young.
Indian Subcontinent: Commercialised dairy sector based on crop by-product feeding with low production per cow. Most bullocks provide draft power and cows provide some milk in farming regions. Small grazing population. Cattle in this region are the smallest compared to cattle found in all other regions.	Dairy	46	Average milk production of 900 kg/head/yr
	Non-Dairy	25	Includes cows, bulls, and young Young comprise a large portion of the population.

TABLE 4-5
MANURE MANAGEMENT EMISSION FACTORS

(kg per head per year)

Livestock	Developed Countries			Developing Countries		
	Cool	Temp.[a]	Warm	Cool	Temp.[a]	Warm
Sheep	0.19	0.28	0.37	0.10	0.16	0.21
Goats	0.12	0.18	0.23	0.11	0.17	0.22
Camels	1.6	2.4	3.2	1.3	1.9	2.6
Horses	1.4	2.1	2.8	1.1	1.6	2.2
Mules and Asses	0.76	1.14	1.51	0.60	0.90	1.2
Poultry[b]	0.078	0.117	0.157	0.012	0.018	0.023

The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15°C; Temperate = 15°C to 25°C inclusive; and Warm = greater than 25°C. The Cool, Temperate and Warm regions are estimated using MCFs of 1 per cent, 1.5 per cent and 2 per cent, respectively.

a Temp. = Temperate climate region.

b Chickens, ducks, and turkeys.

All estimates are ±20 percent.

Sources: Emission factors developed from: feed intake values and feed digestibilities used to develop the enteric fermentation emission factors (see Appendix A); MCF, and B_0 values reported in Woodbury and Hashimoto (1993). All manure is assumed to be managed in dry systems, which is consistent with the manure management system usage reported in Woodbury and Hashimoto (1993).

The ranges of values shown in Table 4-5 reflect the range of Methane Conversion Factor values of 1 to 2 percent. The higher value is appropriate for manure managed in warm climates, while the lower value is appropriate for manure managed in cooler and dryer climates. A middle value is assigned to temperate conditions. The uncertainty in the emission factors remains substantial, however, because field measurements are required to validate the laboratory measurements that form the basis for the MCFs used in the analysis. Appendix B, at the end of this section, summarises the data used to estimate the emission factors shown in Table 4-6.

The climate data collected in Step 1 is used to select the emission factors from Table 4-6. A weighted average emission factor for each animal type is computed by multiplying the percentages of the animal populations in each climate region by the emission factor for each climate region. For example, if sheep in a developing country were 25 percent in a temperate region and 75 percent in a warm region, the emission factor for sheep would be estimated at about 0.2 kg/head/yr as follows:

$$\text{Emission Factor} = (25\% \times 0.16) + (75\% \times 0.21) = 0.1975 \text{ kg/head/yr.}$$

An alternative way of handling these calculations is to sub-divide the category of sheep into two populations: one in warm and one in temperate region. Calculations could then be done separately and summed.

Because the manure from cattle, buffalo, and swine is managed in a variety of ways, including both dry and liquid systems, the variations in manure management practices among regions and countries must be considered to develop emission factors for these animals. Table 4-6 presents emission factors based on regional manure management practices described in Safley et al. (1992).

TABLE 4-6
MANURE MANAGEMENT EMISSION FACTORS FOR CATTLE, SWINE AND BUFFALO

Regional Characteristics	Livestock Type	Emission Factor by Climate Region[a] (kg/head/year)		
		Cool	Temperate	Warm
North America: Liquid-based systems are commonly used for dairy and swine manure. Non-dairy manure is usually managed as a solid and deposited on pastures or ranges.	Dairy Cattle	36	54	76
	Non-Dairy Cattle	1	2	3
	Swine	10	14	18
Western Europe: Liquid/slurry and pit storage systems are commonly used for cattle and swine manure. Limited cropland is available for spreading manure	Dairy Cattle	14	44	81
	Non-Dairy Cattle	6	20	38
	Swine	3	10	19
	Buffalo	3	8	17
Eastern Europe: Solid based systems are used for the majority of manure. About one-third of livestock manure is managed in liquid-based systems.	Dairy Cattle	6	19	33
	Non-Dairy Cattle	4	13	23
	Swine	4	7	11
	Buffalo	3	9	16
Oceania: Virtually all livestock manure is managed as a solid on pastures and ranges. About half of the swine manure is managed in anaerobic lagoons.	Dairy Cattle	31	32	33
	Non-Dairy Cattle	5	6	7
	Swine	20	20	20
Latin America: Almost all livestock manure is managed as a solid on pastures and ranges. Buffalo manure is deposited on pastures and ranges.	Dairy Cattle	0	1	2
	Non-Dairy Cattle	1	2	1
	Swine	0	1	2
	Buffalo	1	1	2
Africa: Almost all livestock manure is managed as a solid on pastures and ranges.	Dairy Cattle	1	1	1
	Non-Dairy Cattle	0	1	1
	Swine	0	1	2
Middle East: Over two-thirds of cattle manure is deposited on pastures and ranges. About one-third of swine manure is managed in liquid-based systems. Buffalo manure is burned for fuel or managed as a solid	Dairy Cattle	1	2	2
	Non-Dairy Cattle	1	1	1
	Swine	1	3	6
	Buffalo	4	5	5
Asia: About half of cattle manure is used for fuel with the remainder managed in dry systems. Almost forty percent of swine manure is managed as a liquid. Buffalo manure is managed in drylots and deposited in pastures and ranges.	Dairy Cattle	7	16	27
	Non-Dairy Cattle	1	1	2
	Swine	1	4	7
	Buffalo	1	2	3
Indian Subcontinent: About half of cattle and buffalo manure is used for fuel with the remainder managed in dry systems. About one-third of swine manure is managed as a liquid.	Dairy Cattle	5	5	6
	Non-Dairy Cattle	2	2	2
	Swine	3	4	6
	Buffalo	4	5	5

[a] Cool climates have an average temperature below 15 C; temperate climates have an average temperature from 15 C to 25 C inclusive, warm climates have an average temperature above 25 'C. All climate categories are not necessarily represented within every region For example, there are no significant warm areas in Eastern or Western Europe Similarly, there are no significant cool areas in Africa and the Middle East. See Appendix B for the derivation of these emission factors

Note: Significant buffalo populations do not exist in North America, Oceania, or Africa.

As shown in the table, the emission factors for dairy cattle range between 81 kg/head/year in warm parts of Western Europe to 0 kg/head/year in cool parts of Latin America. The emission factors for non-dairy cattle range between 38 kg/head/yr in warm parts of Western Europe to 1 kg/head/year in cool parts of North America and Latin America. In addition to climate, the range of emission factors is due to the manure management practices used in each region. For example, the emission factors for North American dairy cattle manure and European dairy and non-dairy cattle manure are relatively high because the manure is often managed using liquid systems that promote methane production. The emission factors for North American non-dairy cattle and for all animals in Africa and the Middle East are relatively low because their manure is generally managed using dry systems that do not promote methane production.

To select emission factors from Table 4-6, first identify the appropriate region, such as Latin America. Within that region, identify the animal type of interest. For that animal type three values are given for the three climate regions. Compute a weighted average emission factor for the animal type by multiplying the percentages of the animal population in each climate region by the emission factor for each climate region. Appendix B summarises the estimates of manure management system usage and MCFs that underlie the emission factors in Table 4-6.

As with the other manure management emission factors, there is substantial uncertainty in the estimates shown in Table 4-6 because field measurements are required to validate the laboratory measurements that form the basis for the MCFs used in the analysis, and because there is uncertainty and variability in the manner in which manure is managed in each region.

TIER 1: STEP 3 – TOTAL EMISSION

To estimate total emission the selected emission factors are multiplied by the associated animal population and summed. The emission estimates should be reported in gigagrams (Gg). Because the emission factors are reported in kilograms per head per year, the total emissions in Gg is estimated as follows for each animal category:

emission factor (kg/head/year) x population (head) / (10^6 kg/Gg)
= emissions Gg/year.

As a point of reference, in 1990 total annual global methane emissions from domestic livestock enteric fermentation were on the order of 0.060 to 0.100 Gg (Gibbs and Johnson, 1993). Enteric fermentation emissions from countries with large populations of livestock may be on the order of 0.001 to 0.005 Gg per year. Countries with smaller populations of livestock would likely have emissions of less than 0.001 Gg per year.

In 1990 total annual global methane emissions from manure management was on the order of 0.010 to 0.018 Gg (Woodbury and Hashimoto, 1993). Manure management emissions from countries where manure is managed in liquid-based systems may be on the order of 0.001 to 0.002 Gg per year. Countries where manure is not managed in liquid-based systems would likely have emissions of much less than 0.001 Gg per year.

4.2.4 Tier 2 Approach For Enteric Fermentation Emissions

The Tier 2 approach is recommended for estimating methane emissions from enteric fermentation from cattle for those countries with large cattle populations. As contrasted with the Tier 1 method, this approach requires much more detailed information on the cattle population. Using this detailed information, more precise estimates of the cattle emission factors are developed. When the Tier 2 method is used the default emission factors listed in Tier 1 for cattle are not used.

This Tier 2 approach is similar to the August 1991 OECD method (OECD. 1991), with some modifications:

- The Blaxter and Clapperton (1965) equation is replaced with a recommended set of methane conversion rate "rules of thumb."
- Feed energy intake requirements for pregnancy have been added
- The energy requirements required for grazing have been reduced based on newly available data from AAC (1990).
- The equations used to relate gross energy intake to net energy used by the animal have been made more general to fit a wider variety of feed conditions.

The three steps outlined for Tier I are also used here.

ENTERIC FERMENTATION TIER 2: STEP I – LIVESTOCK POPULATION

To develop precise estimates of emissions, cattle should be divided into categories of relatively homogeneous groups. For each category a representative animal is chosen and characterised for the purpose of estimating an emission factor. Table 4-7 presents a set of recommended representative cattle types. Three main categories, Mature Dairy Cattle, Mature Non-Dairy Cattle, and Young Cattle, are recommended as the minimum set of representative types. The subcategories listed should be used when data are available. In particular, the sub-population of cows providing milk to calves should be identified among non-dairy cattle because the feed intake necessary to support milk production can be substantial. In some countries the feedlot category is needed so that the implications of the high-grain diets can be incorporated.

TABLE 4-7
RECOMMENDED REPRESENTATIVE CATTLE TYPES

Main Categories	Subcategories
Mature Dairy Cattle	Dairy Cows used principally for commercial milk production
Mature Non-Dairy Cattle	Mature Females: • **Beef Cows**: used principally for producing beef steers and heifers • **Multiple-Use Cows**. used for milk production, draft power, and other uses Mature Males: • **Breeding Bulls**: used principally for breeding purposes • **Draft Bullocks**: used principally for draft power
Young Cattle	Pre-Weaned Calves Growing Heifers, Steers/Bullocks and Bulls Feedlot-Fed Steers and Heifers on High-Grain Diets

For each of the representative animal types defined, the following information is required:

- annual average population (number of head);
- average daily feed intake (megajoules (MJ) per day and kg per day of dry matter); and
- methane conversion rate (percentage of feed energy converted to methane).

Generally, data on average daily feed intake are not available, particularly for grazing animals. Consequently, the following data should be collected for estimating the feed intake for each representative animal type[4]:

- weight (kg);
- average weight gain per day (kg);[5]
- feeding situation: confined animals; animals grazing good quality pasture; and animals grazing over very large areas;
- milk production per day (kg/day);[6]
- average amount of work performed per day (hours/day);
- percentage of cows that give birth in a year;[7] and
- feed digestibility (%).[8]

These data should be obtained from country-specific cattle evaluations. Some data, such as weight, weight gain, and milk production, may be available from production statistics. Care should be taken to use the live cattle weights, as contrasted with slaughter weights. Appendix A, at the end of this section, lists the data used to develop the default emission factors presented in Tier 1. Individual country data can be compared to the data presented in Appendix A to ensure that the data collected are reasonable.

Data on methane conversion rates are also not generally available. The following rules of thumb are recommended for the methane conversion rates:

- Developed Countries. A 6 per cent conversion rate (±0.5 per cent) is recommended for all cattle in developed countries except feedlot cattle consuming diets with a large quantity of grain. For feedlot cattle on high grain diets a rate of 4 per cent (±0.5 per cent) is recommended. In circumstances where good feed is available (i.e., high digestibility and high energy value) the lower bounds of these ranges can be used. When poorer feed is available, the higher bounds are more appropriate.
- Developing Countries. Several recommendations are made for different animal management situations in developing countries:
  - All dairy cows and young cattle are recommended to have a conversion rate of 6.0 per cent (±0.5 per cent). These cattle are generally the best-fed cattle in these regions.
  - All non-dairy cattle, other than young stall-fed animals, consuming low-quality crop by-products are recommended to have a conversion rate of 7.0 per

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[4] In many, if not most, cattle management circumstances, the principal driving factors that affect feed intake are: weight, milk production and feed digestibility.

[5] This may be assumed to be zero for mature animals.

[6] Milk production is required for dairy cows and non-dairy cows providing milk to calves.

[7] This is only relevant for mature cows.

[8] Feed digestibility is defined as the proportion of energy in the feed that is not excreted in the faeces. Digestibility is commonly expressed as a percentage (%). Common ranges for feed digestibility for cattle are 50% to 60% for crop by-products and rangelands; 60% to 70% for good pastures, good preserved forages, and grain-supplemented forage-based diets; and 75% to 85% for grain-based diets fed in feedlots.

cent (±0.5 per cent) because feed resources are particularly poor in many cases in these regions.

- Grazing cattle are recommended to have a conversion rate of 6.0 per cent (±0.5 per cent), except for grazing cattle in Africa, which are recommended to have a rate of 7.0 per cent (±0.5 per cent) because of the forage characteristics found in many portions of tropical Africa.

These rules of thumb are a rough guide based on the general feed characteristics and production practices found in many developed and developing countries. Country-specific exceptions to these general rules of thumb should be taken into consideration as necessary based on detailed data from cattle experts.

ENTERIC FERMENTATION TIER 2: STEP 2 – EMISSION FACTORS

The emission factors for each category of cattle are estimated based on the feed intake and methane conversion rate for the category. Feed intake is estimated based on the feed energy requirements of the representative animals, subject to feed-intake limitations. The net energy system described in NRC (1984 and 1989) is recommended as the starting point for the estimates. Because the NRC system was developed for feeding conditions in temperate regions, several adjustments were made to avoid potential biases when applied to evaluate feed-energy intakes for tropical cattle (see Appendix C). Comparisons with alternative feeding systems (e.g., ARC, 1980) indicate that the emissions estimates are not sensitive to the feeding system used as the basis for making the estimates.

The net energy system specifies the amount of feed energy required for the physiological functions of cattle, including maintenance, growth, and lactation. Feed energy requirements for work have also been estimated, and are included in this analysis for the draft animals in developing countries. Energy requirements for pregnancy have also been added for the portion of cows that give birth in each year. The following information is required to estimate feed energy intakes:

- *Maintenance*

  Maintenance refers to the apparent feed energy required to keep the animal in energy equilibrium, i.e., there is no gain or loss of energy in the body tissues (Jurgens, 1988). For cattle, net energy for maintenance (NE_m) has been estimated to be a function of the weight of the animal raised to the 0.75 power (NRC, 1984):

EQUATION 1

$$NE_m \text{ (MJ/day)} = 0.322 \times (\text{weight in kg})^{0.75}$$

NRC (1989) recommends that lactating dairy cows be allowed a slightly higher maintenance allowance:

$$NE_m \text{ (MJ/day)} = 0.335 \times (\text{weight in kg})^{0.75} \quad \{\text{dairy cows}\}$$

- *Feeding*

  Additional energy is required for animals to obtain their food. Grazing animals require more energy for this activity than do stall-fed animals. The following energy requirements are added for this activity based on their feeding situation:[9]

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[9] The original OECD method recommended slightly higher energy additions. These revised figures are based on newly-published information in AAC (1990).

EQUATION 2

NE_{feed} =

Confined animals (pens and stalls): no additional NE_m;

Animals grazing good quality pasture: 17 per cent of NE_m; and

Animals grazing over very large areas: 37 per cent of NE_m.

- *Growth*

  The energy requirements for growth can be estimated as a function of the weight of the animal and the rate of weight gain. NRC (1989) presents formulae for large- and small-frame males and females, the estimates from which vary by about ± 25 per cent. The equation for large-frame females is recommended, which is about the average for the four types:

  EQUATION 3

  $$NE_g \text{ (MJ/day)} = 4.18 \times \{(0.035\ W^{0.75} \times WG^{1.119}) + WG\}$$

  where:

  W = animal weight in kilograms (kg); and

  WG = weight gain in kg per day.

  The relationships for NE_g were developed for temperate agriculture conditions, and may over-estimate energy requirements for tropical conditions, particularly for draft animals that may have a lower fat content in their weight gain (Graham, 1985). However, no data are available for improving the estimates at this time.

- *Lactation*

  Net energy for lactation has been expressed as a function of the amount of milk produced and its fat content (NRC, 1989):

  EQUATION 4

  $$NE_l \text{ (MJ/day)} = \text{kg of milk/day} \times (1.47 + 0.40 \times \text{Fat \%})$$

  At 4.0 per cent fat, the NE_l in MJ/day is about 3.1 x kg of milk per day.

- *Draft Power*

  Various authors have summarised the energy intake requirements for providing draft power (e.g., Lawrence, 1985; Bamualim and Kartiarso, 1985; and Ibrahim, 1985). The strenuousness of the work performed by the animal influences the energy requirements, and consequently a wide range of energy requirements have been estimated. The values by Bamualim and Kartiarso show that about 10 per cent of NE_m requirements are required per hour of typical work for draft animals. This value is used as follows:

  EQUATION 5

  $$NE_{draft} \text{ (MJ/day)} = 0.10 \times NE_m \times \text{hours of work per day}$$

- *Pregnancy*

  Daily energy requirements for pregnancy are presented in NRC (1984). Integrating these requirements over a 281-day gestation period yields the following equation:

Equation 6

$$NE_{pregnancy}\ (MJ/281\text{-day period}) = 28 \times \text{calf birth weight in kg}$$

The following equation can be used to estimate the approximate calf birth weight as a function of the cow's weight:[10]

Equation 7

$$\text{Calf birth weight (kg)} = 0.266 \times (\text{cow weight in kg})^{0.79}$$

Manipulating Equations 6 and 7, in conjunction with Equation 1, shows that the NE required for pregnancy is about 7.5 per cent of NE_m for the range of cow sizes considered in this analysis. Therefore, a factor of 7.5 per cent of NE_m is added to account for the energy required for pregnancy for the portion of cows giving birth each year.

Based on these equations, each of the net energy components for each of the cattle categories can be estimated from the data collected in Step 1: weight in kilograms; feeding situation; weight gain per day in kilograms; milk production in kilograms of 4 per cent fat-corrected milk; number of hours of work performed per day; and portion that give birth.

These net energy requirements must be translated into gross energy intakes. Also, by estimating the gross energy intake, the net energy estimates can be checked for reasonableness against expected ranges of feed intake as a percentage of animal weight. To estimate gross energy intake, the relationship between the net energy values and gross energy values of different feeds must be considered. This relationship can be summarised briefly as follows:

Digestible Energy = Gross Energy - Faecal Losses
Metabolisable Energy = Digestible Energy - Urinary and Combustible Gas Losses
Net Energy = Metabolisable Energy - Heat Increment

Net Energy = Gross Energy - Faecal Losses - Urinary and Combustible Gas Losses - Heat Increment

The quantitative relationship among these energy values varies among feed types. Additionally, the values depend on how the feeds are prepared and fed, and the level at which they are fed. For purposes of this method, simplifying assumptions are used to derive a relationship between net energy and digestible energy that is reasonably representative for the range of diets typically fed to cattle. Gross energy intake is then estimated using this relationship and the digestibility data collected in Step 1.

Given the digestibility of the feed (defined in Step 1), a general relationship between digestible energy and metabolisable energy can be used as follows (NRC, 1984):

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[10] This species-specific equation from Robbins and Robbins (1979) was adjusted to the mean cow and calf weight of a typical beef breed of cattle. This adjustment increases the coefficient in the equation from 0.214 to 0.266.

EQUATION 8

$$\text{Metabolisable Energy (ME)} = 0.82 \times \text{Digestible Energy (DE)}$$

Equation 8 is a simplified relationship; larger (smaller) methane conversion rates would tend to reduce (increase) the coefficient to values below (above) 0.82.

NRC (1984) presents separate quantitative relationships between metabolisable energy and net energy used for growth versus net energy used for other functions. Using Equation 8, the NRC relationships can be re-arranged to quantify the ratio of NE to DE, as follows:

EQUATION 9

$$NE/DE = 1.123 - (4.092 \times 10^{-3} \times DE\%) + (1.126 \times 10^{-5} \times (DE\%)^2) - 25.4/DE\%$$

EQUATION 10

$$NE_g/DE = 1.164 - (5.160 \times 10^{-3} \times DE\%) + (1.308 \times 10^{-5} \times (DE\%)^2) - 37.4/DE\%$$

where:

NE/DE = the ratio of net energy consumed for maintenance, lactation, work and pregnancy to digestible energy consumed;

NE_g/DE = the ratio of net energy consumed for growth to digestible energy consumed; and

$DE\%$ = digestible energy as percentage of gross energy, expressed in per cent (e.g., 65%).

Because the NRC (1984) relationships were developed based on diets with relatively high digestibilities (generally above 65 per cent), they may not be appropriate for the relatively low digestibility diets that are commonly found in tropical livestock systems. In particular, the non-linear nature of the relationships could appear to increase the estimates of feed intake for low-digestibility feeds. An apparent increase in feed intake would lead to an apparent increase in emissions estimates.

Based on a review of other energy systems (e.g., ARC, 1980), a linear relationship between digestible energy and net energy was derived for digestibilities below 65 per cent as follows (see Appendix C):

EQUATION 11

$$NE/DE = 0.298 + (0.00335 \times DE\%)$$

EQUATION 12

$$NE_g/DE = -0.036 + (0.00535 \times DE\%)$$

Given the estimates for feed digestibility (from Step 1) and equations 9 through 12, the gross energy intake (GE in MJ/day) can be estimated as follows:

EQUATION 13

$$GE = \frac{\left(NE_m + NE_{feed} + NE_l + NE_{draft} + NE_{pregnancy}\right) \times \left(100/_{DE\%}\right)}{\left(NE/_{DE}\right) + \left(NE_g/_{\{NE_g/DE\}}\right)}$$

where:

{*NE/DE*} is computed from equation 9 for digestibility greater than 65 per cent and from equation 11 for digestibility less than or equal to 65 per cent;

{*NE$_g$/DE*} is computed from equation 10 for digestibility greater than 65 per cent and from equation 12 for digestibility less than or equal to 65 per cent; and

DE% is digestibility in percent (e.g., 60%).

To check the estimate of daily gross energy intake from Equation 13, the estimate can be converted in daily intake in kilograms by dividing by 18.45 MJ/kg. This estimate of intake in kilograms should generally be between 1.5 per cent and 3.0 per cent of the animal's weight.

Using Equation 13 and the cattle data summarised in Appendix A, Gibbs and Johnson (1993) found that the intake estimates are consistent with expected intakes as a percentage of body weight and previously published values. For example, the intake estimate for Indian cattle is the equivalent of about 10,000 MJ per year of metabolisable energy (ME). Winrock (1978) estimates the average ME requirements for Indian cattle at 10,600 MJ per year. Similarly, the ME values implied for US dairy and non-dairy cows are 58,000 MJ and 31,000 MJ per year, respectively, which are similar to estimates of 62,000 MJ and 31,700 MJ derived in US EPA (1993). Consequently, for a diverse set of conditions, the intake estimates correspond to reasonably expected ranges from previously published estimates.

To estimate the emission factor for each cattle type, the feed intake is multiplied by the methane conversion rate (from Step 1) as follows:

EQUATION 14

Emissions (kg/yr) = [Intake (MJ/day) x Y_m x (365 days/yr)] / [55.65 MJ/kg of methane]

where Y_m is the methane conversion rate expressed in decimal form (such as 0.06 for 6 per cent). The result of this step of the method is an emission factor for each cattle type defined in Step 1.

ENTERIC FERMENTATION TIER 2: STEP 3 – TOTAL EMISSIONS

To estimate total emissions the selected emission factors are multiplied by the associated animal population and summed. As described above under Tier 1, the emissions estimates should be reported in gigagrams (Gg).

4.2.5 Tier 2 Approach For Manure Management Emissions

The Tier 2 approach provides a more detailed method for estimating methane emissions from manure management systems. The Tier 2 approach is recommended for countries with large cattle, buffalo and swine populations managed under confined conditions. Compared to the Tier 1 approach, this method requires additional detailed information on animal characteristics and the manner in which manure is managed. Using this additional information, emission factors are estimated that are specific to the conditions of the country, and the default emission factors from Tier 1 are not used.

The Tier 2 approach is similar to the original OECD method described in OECD (1991). Improvements to the method have been made to incorporate more recent figures on methane conversion factors and to link the method more closely to the animal characteristic data collected for estimating enteric fermentation.

MANURE MANAGEMENT TIER 2: STEP 1 – LIVESTOCK POPULATIONS

To develop precise estimates of emissions, the animals should be divided into relatively homogeneous groups. For each category a representative animal is chosen and characterised for purposes of estimating an emission factor. Suggested categories for cattle are discussed above under the enteric fermentation Tier 2 method and are summarised in Table 4-7. Similar categories can be used for buffalo. Categories for swine could include sows, boars, and growing animals (farrows to finishers). For each of the representative animal types defined, the following information is required:

- annual average population (number of head) by climate region (cool, temperate, and warm);
- average daily volatile solids (VS) excretion (kg of dry matter per day);[11]
- methane-producing potential (B_o) of the manure (cubic metres (m^3) of methane per kg of VS);
- manure management system usage (percentage of manure managed with each management system).

Population data are generally available from country-specific livestock census reports. As described above under Tier 1, the portion of each animal population in cool, temperate, and warm climate regions is required.

Often, data on average daily VS excretion are not available. Consequently, the VS values may need to be estimated from feed intake levels. The enteric fermentation Tier 2 method should be used to estimate feed intake levels for cattle and buffalo.[12] For swine, country-specific swine production data may be required to estimate feed intake. To develop the default emission factors for swine presented in Tier 1, average feed intake estimates for swine in developed and developing countries were used from Crutzen et al. (1986) (see Appendix B, at the end of this section).

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[11] Volatile solids (VS) are the degradable organic material in livestock manure.

[12] By using the enteric fermentation Tier 2 method to estimate feed intake, consistency is assured in the data underlying the emissions estimates for both enteric fermentation and manure management.

Once feed intake is estimated, the VS excretion rate is estimated as:[13]

EQUATION 15

$$\text{VS (kg dm/day)} = \text{Intake (MJ/day)} \times (1 \text{ kg}/18.45 \text{ MJ}) \times (1 - \text{DE\%}/100) \times (1 - \text{ASH\%}/100)$$

where:

VS = VS excretion per day on a dry weight basis;

dm = dry matter

Intake = the estimated daily average feed intake in MJ/day;

DE% = the digestibility of the feed in percent (e.g., 60%);

ASH% = the ash content of the manure in percent (e.g., 8%).

For cattle, the DE% value used should be the same value used to implement Tier 2 for enteric fermentation. The ash content of cattle and buffalo manure is generally around 8 per cent. For swine, the default emission factors were estimated using 75 per cent and 50 per cent digestibility for developed and developing countries, respectively, and an ash content of 2 per cent and 4 per cent for developed and developing countries, respectively. Appendix B summarises the data used to estimate the VS excretion rates for cattle, buffalo, and swine.

The maximum methane-producing capacity for the manure (B_o) varies by species and diet. Country-specific data should be used where feasible. A range of representative B_o values for cattle, buffalo, and swine populations were used to develop the default emission factors as follows (see Appendix B):

- Dairy Cattle
  - Developed Countries: 0.24 m^3/kg VS
  - Developing Countries: 0.13 m^3/kg VS
- Non-Dairy Cattle
  - Developed Countries: 0.17 m^3/kg VS
  - Developing Countries: 0.10 m^3/kg VS
- Buffalo in all regions: 0.10 m^3/kg VS
- Swine
  - Developed Countries: 0.45 m^3/kg VS
  - Developing Countries: 0.29 m^3/kg VS

The portion of manure managed in each manure management system must also be collected for each representative animal type. Table 4-8 summarises the main types of manure management systems. The first four types in the table, pasture, daily spread, solid storage, and drylot are all dry manure management systems. These systems produce little or no methane. The wet manure management systems, liquid/slurry, anaerobic lagoon, and pit storage are the primary sources of manure methane emissions. To implement this Tier 2 method, at a minimum the proportion of manure managed in wet and dry systems must be estimated.

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[13] The energy density of feed is about 18.45 MJ per kg of dry matter. This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

TABLE 4-8
MANURE MANAGEMENT SYSTEMS AND METHANE CONVERSION FACTORS (MCFs)

System		MCF by Climate[a]			Source
		Cool	Temperate	Warm	
Pasture/Range/Paddock: The manure from pasture and range grazing animals is allowed to lie as is, and is not managed.		1%	1.5%	2%	b
Daily Spread Manure is collected in solid form by some means such as scraping. The collected manure is applied to fields regularly (usually daily).		0.1%	0.5%	1%	b
Solid Storage: Manure is collected as in the daily spread system, but is stored in bulk for a long period of time (months) before any disposal.		1%	1.5%	2%	b
Drylot In dry climates animals may be kept on unpaved feedlots where the manure is allowed to dry until it is periodically removed. Upon removal the manure may be spread on fields.		1%	1.5%	5%	b
Liquid/Slurry These systems are characterised by large concrete lined tanks built into the ground. Manure is stored in the tank for six or more months until it can be applied to fields. To facilitate handling as a liquid, water may be added to the manure.		10%	35%	65%	b
Anaerobic Lagoon Anaerobic lagoon systems are characterised by flush systems that use water to transport manure to lagoons. The manure resides in the lagoon for periods from 30 days to over 200 days. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.		90%	90%	90%	c
Pit Storage Liquid swine manure may be stored in a pit while awaiting final disposal. The length of storage time varies, and for this analysis is divided into two categories: less than one month or greater than one month	< 30 Days	5%	18%	33%	b
	> 30 Days	10%	35%	65%	b
Anaerobic Digester The manure, in liquid or slurry form, is anaerobically digested to produce methane gas for energy. Emissions are from leakage and vary with the type of digester.		5-15%	5-15%	5-15%	d
Burned for Fuel Manure is collected and dried in cakes and burned for heating or cooking. Emissions occur while the manure is stored before it is burned. Methane emission associated with the combustion of the manure are not considered here Combustion-related emissions are estimated in the *Traditional Biomass Fuels* section of the *Energy* chapter.		5-10%	5-10%	5-10%	e

a Cool climates have an average temperature below 15 C, temperate climates have an average temperature from 15°C to 25°C inclusive; warm climates have an average temperature above 25° C.

b Hashimoto and Steed (1993).

c Safley et al., (1992) and Safley and Westerman (1992)

d Yancun et al. (1985), Stuckey (1984) and Lichtman (1983).

e Safley et al (1992).

The default emission factors presented in Tier 1 are based on manure management system usage data collected by Safley et al. (1992). Appendix B presents these data by region for cattle, buffalo, and swine. Although the data in Appendix B can be used as defaults, country-specific data, e.g., obtained through a survey, would improve the basis for implementing the Tier 2 method. The resulting estimates must show the portion of manure from each animal type managed within each management system, by climate region.

MANURE MANAGEMENT TIER 2: STEP 2 – EMISSION FACTORS

Emission factors are estimated for each animal type based using the data collected in Step 1 and the methane conversion factors (MCFs) for each manure management system. The MCF defines the portion of the methane producing potential (B_o) that is achieved. The MCF varies by manure management system and climate and can range between 0 and 100 per cent. Table 4-8 presents the latest available MCF estimates for the major manure management systems that have been developed.

To calculate the emission factor for each animal type, a weighted average methane conversion factor (MCF) is calculated using the estimates of the manure managed by waste system within each climate region. The average MCF is then multiplied by the VS excretion rate and the B_o for the animal type. In equation form, the estimate is as follows:

EQUATION 16

$$EF_i = VS_i \times 365 \text{ days/year} \times B_{oi} \times 0.67 \text{ kg/m}^3 \times \sum_{jK} MCF_{jK} \times MS\%_{ijK}$$

where:

EF_i = annual emission factor (kg) for animal type *i* (e.g., dairy cows);

VS_i = daily VS excreted (kg) for animal type *i*;

B_{oi} = maximum methane producing capacity (m^3/kg of VS) for manure produced by animal type *i*;

MCF_{jk} = methane conversion factors for each manure management system *j* by climate region *k*; and

$MS\%_{ijk}$ = fraction of animal type *i*'s manure handled using manure system *j* in climate region *k*.

MANURE MANAGEMENT TIER 2: STEP 3 – TOTAL EMISSIONS

To estimate total emissions the selected emission factors are multiplied by the associated animal population and summed. As described above under Tier 1, the emissions estimates should be reported in gigagrams (Gg).

4.2.6 Beyond Tier 2

The default values used in the Tier 1 and 2 methods were derived from available livestock and manure management data and are generally representative of regional conditions. Because livestock and manure management conditions can vary significantly across and within countries, the default values may not reflect adequately the conditions in a given country. Additionally, the variability of conditions has not been well characterised to date.

The emissions estimates can be improved by going beyond the Tier 2 default data and collecting key country- or region-specific data. Data elements that would benefit from data collection initiatives (such as targeted surveys of major livestock types) include the following:

- *Cattle weight*
  In many regions the weights of cattle are not well quantified.
- *Feed intake*
  Field data on feed intake would be valuable for validating the feed intake estimates made under Tier 2 for cattle.
- *Manure production*
  Field data on manure production by livestock would be valuable for validating the manure production estimates made under Tier 2.
- *Manure management*
  Field data on manure management system usage would improve the basis for making the estimates. Considerations of seasonal management practices could be incorporated into the data.

In addition to these data collection initiatives, measurement programs can be used to improve the basis for making the estimates. In particular, measurements of emissions from manure management systems under field conditions is needed. Techniques for making these measurements are described in IAEA (1992). Additionally, measurements of the maximum methane producing ability of manure (B_o) from livestock in tropical regions is needed.

Additionally, new techniques are being deployed to measure emissions from cattle under field conditions (Johnson et al., 1993). Using these techniques, coefficients used in Tier 2 can be verified (such as the methane conversion rate) and the emissions estimates can be validated. Targeted assessments of tropical cattle populations would be most valuable.

Appendix A

Data Underlying Default Emission Factors for Enteric Fermentation

This appendix presents the data used to develop the default emission factors for methane emissions from enteric fermentation. The detailed information presented for cattle and buffalo was developed in Gibbs and Johnson (1993). The Tier 2 method was implemented with these data to estimate the default emission factors for cattle and buffalo. Also presented are the summary data from Crutzen et *al*. (1986) that were used to estimate the emission factors for the other species.

TABLE A-1

DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR DAIRY CATTLE

Regions	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digestibility of Feed %	CH_4 Conversion %
North America[a]	600	0	Stall Fed	18.4	0	90%	65%	6%
Western Europe	550	0	Stall Fed	11.5	0	90%	60%	6%
Eastern Europe[b]	550	0	Stall Fed	7.0	0	80%	60%	6%
Oceania[c]	500	0	Stall Fed	4.7	0	80%	60%	6%
Latin America[d]	400	0	Pasture/Range	2.2	0	80%	60%	6%
Asia[e]	350	0	Stall Fed	4.5	0	80%	60%	6%
Africa & Middle East	275	0	Stall Fed	1.3	0	67%	60%	6%
Indian Subcontinent[f]	275	0	Stall Fed	2.5	0	50%	55%	6%

a Based on estimates for the United States

b Based on estimates for the former USSR

c Based on estimates for Australia.

d Based on estimates for Brazil.

e Based on estimates for China.

f Based on estimates for India.

Source: Gibbs and Johnson (1993).

TABLE A-2
DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR NON-DAIRY CATTLE

Type	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digestibility of Feed %	CH_4 Conversion %	Day Weighted Population Mix %	Emission Factors kg/head/yr
North America[a]										
Mature Females	500	0.0	Pasture/Range	3.3	0.0	80%	60%	6.0%	36%	69
Mature Males	800	0.0	Pasture/Range	0.0	0.0	0%	60%	6.0%	2%	75
Calves on milk	100	0.9	Pasture/Range	0.0	0.0	0%	NA	0.0%	16%	0
Calves on forage	185	0.9	Pasture/Range	0.0	0.0	0%	65%	6.0%	8%	42
Growing heifers/steers	265	0.7	Pasture/Range	0.0	0.0	0%	65%	6.0%	17%	47
Replacement/growing	375	0.4	Pasture/Range	0.0	0.0	0%	60%	6.0%	11%	56
Feedlot cattle	415	1.3	Stall Fed	0.0	0.0	0%	75%	3.5%	11%	37
Western Europe										
Mature Males	600	0.0	Pasture/Range	0.0	0.0	0%	60%	6.0%	22%	60
Replacement/growing	400	0.4	Pasture/Range	0.0	0.0	0%	60%	6.0%	54%	84
Calves on milk	230	0.3	Pasture/Range	0.0	0.0	0%	65%	0.0%	15%	0
Calves on forage	230	0.3	Pasture/Range	0.0	0.0	0%	65%	6.0%	8%	33
Eastern Europe[b]										
Mature Females	500	0.0	Pasture/Range	3.3	0.0	67%	60%	6.5%	30%	74
Mature Males	600	0.0	Pasture/Range	0.0	0.0	0%	60%	6.5%	22%	65
Young	230	0.4	Pasture/Range	0.0	0.0	0%	60%	6.0%	48%	40
Oceania[c]										
Mature Females	400	0.0	Pasture/Range	2.4	0.0	67%	55%	6.0%	51%	63
Mature Males	450	0.0	Pasture/Range	0.0	0.0	0%	55%	6.0%	11%	55
Young	200	0.3	Pasture/Range	0.0	0.0	0%	55%	6.0%	38%	39

[a] Based on estimates for the United States.

[b] Based on estimates for the former USSR

[c] Based on estimates for Australia

TABLE A-2 (CONTINUED)

DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR NON-DAIRY CATTLE

Type	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digestibility of Feed %	CH4 Conversion %	Day Weighted Population Mix %	Emission Factors kg/head/yr
Latin America[d]										
Mature Females	400	0.0	Large Areas	1.1	0.0	67%	60%	6.0%	37%	58
Mature Males	450	0.0	Large Areas	0.0	0.0	0%	60%	6.0%	6%	57
Young	230	0.3	Large Areas	0.0	0.0	0%	60%	6.0%	58%	42
Asia[e]										
Mature Females-Farming	325	0.0	Stall Fed	1.1	0.55	33%	55%	6.5%	27%	48
Mature Females-Grazing	300	0.0	Pasture/Range	1.1	0.00	50%	60%	6.0%	9%	41
Mature Males-Farming	450	0.0	Stall Fed	0.0	1.37	0%	55%	6.5%	24%	58
Mature Males-Grazing	400	0 0	Pasture/Range	0.0	0.00	0%	60%	6.0%	8%	44
Young	200	0.2	Pasture/Range	0.0	0.00	0%	60%	6.0%	32%	31
Africa										
Mature Females	200	0.0	Stall Fed	0.3	0.55	33%	55%	6.5%	13%	31
Draft Bullocks	275	0.0	Stall Fed	0.0	1.37	0%	55%	6.5%	13%	40
Mature Females-Grazing	200	0.0	Large Areas	0.3	0.00	33%	55%	7.5%	6%	46
Bulls - Grazing	275	0.0	Large Areas	0.0	0.00	0%	55%	7.5%	25%	55
Young	75	0.1	Pasture/Range	0.0	0.00	0%	60%	6.0%	44%	14
Indian Subcontinent[f]										
Mature Females	125	0.0	Stall Fed	0.6	0.00	33%	50%	7.5%	40%	31
Mature Males	200	0.0	Stall Fed	0.0	2.74	0%	50%	7.5%	10%	41
Young	80	0.1	Stall Fed	0.0	0.00	0%	50%	6.0%	50%	17

d Based on estimates for the Brazil.

e Based on estimates for the China.

f Based on estimates for India.

Source: Gibbs and Johnson (1993).

TABLE A-3

DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR BUFFALO

Type	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digestibility of Feed %	CH_4 Conversion %	Population Mix %	Emissions Factors kg/head/year
Indian Subcontinent[a]										
Adult Males	350 - 550	0.00	Stall Fed	0.00	1.37	0%	55%	7.5	14%	55 - 77
Adult Females	250 - 450	0.00	Stall Fed	2.70	0.55	33%	55%	7.5	40%	57 - 80
Young	100 - 300	0.15	Stall Fed	0.00	0.00	0%	55%	7.5	46%	23 - 50
Other Countries[b]										
Adult Males	350 - 550	0.00	Stall Fed	0.00	1.37	0%	55%	7.5	45%	55 - 77
Adult Females	250 - 450	0.00	Stall Fed	0.00	0.55	25%	55%	7.5	45%	45 - 67
Young	100 - 300	0.15	Stall Fed	0.15	0.00	0%	55%	7.5	10%	23 - 50

[a] Based on estimates for India.

[b] Based on estimates for China.

Source: Gibbs and Johnson (1993).

TABLE A-4
DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR OTHER ANIMALS

Animal Type		Feed Intake (MJ/head/day)	Methane Conversion Factor (%)
Sheep	Developed Countries	20	6%
	Developing Countries	13	6%
Goats	Developed Countries	14	5%
	Developing Countries	14	5%
Camels	Developed Countries	100	7%
	Developing Countries	100	7%
Horses	Developed Countries	110	2.5%
	Developing Countries	110	2.5%
Mules/Asses	Developed Countries	60	2.5%
	Developing Countries	60	2.5%
Swine	Developed Countries	38	0.6%
	Developing Countries	13	1.3%
Poultry	Developed Countries	Not Estimated	
	Developing Countries		

Sources: Feed intake and methane conversion for all animals from Crutzen et al (1986). Methane conversion for camels modified as in Gibbs and Johnson (1993).

Appendix B

Data Underlying Default Emission Factors for Manure Management

This appendix presents the data used to develop the default emission factors for methane emissions from manure management. The detailed information presented for cattle and buffalo were developed in Gibbs and Johnson (1993). The swine feed intake data are from Crutzen et al. (1986). The manure management system usage data and B_o estimates are from Safley et al. (1992). The methane conversion factor (MCF) data are from Woodbury and Hashimoto (1993). The Tier 2 method was implemented with these data to estimate the default emission factors for cattle, buffalo, and swine. Also presented are the summary feed intake data from Crutzen et al. (1986) and the manure-related data from Safley et al. (1992) and Woodbury and Hashimoto (1993) that were used to estimate the emission factors for the other species.

TABLE B-1
FEED INTAKE AND MANURE PRODUCTION FOR CATTLE

Region	Livestock Category	Sub-Population	Mass (kg)	Feed Digest. (%)	Energy Intake (MJ/day)	Feed Intake (kg/day)	Pct of Category Population	Manure (kg/h/d dm)	VS (kg/h/d)	Bo (m^3 CH_4/kg VS)
North America	Dairy Cattle	Average	600	65%	299.5	16.2	100%	5.68	5.23	0.24
	Non-Dairy Cattle	Mature Females	500	60%	174.0	9.4	36%	3.77	3.47	0.17
		Mature Males	800	60%	189.3	10.3	2%	4.10	3.78	0.17
		Young on milk	100	NA	NA	NA	15%	negligible	negligible	0.17
		Young	185	65%	107.2	5.8	8%	2.03	1.87	0.17
		Young	265	65%	120.1	6.5	17%	2.28	2.10	0.17
		Young	375	60%	143.2	7.8	11%	3.10	2.86	0.17
		Feedlot	415	75%	161.8	8.8	11%	2.19	2.02	0.17
		Avg. Non-Dairy Cattle	357	53%	128.0	6.9	100%	2.55	2.35	0.17
Western Europe	Dairy Cattle	Average	550	60%	254.7	13.8	100%	5.52	5.08	0.24
	Non-Dairy Cattle	Mature Males	600	60%	152.5	8.3	22%	3.31	3.04	0.17
		Young Replacements	400	60%	149.8	8.1	55%	3.25	2.99	0.17
		Young Calves	230	65%	83.7	4.5	23%	1.59	1.46	0.17
		Avg. Non-Dairy Cattle	405	61%	135.1	7.3	100%	2.88	2.65	0.17
Eastern Europe	Dairy Cattle	Average	550	60%	207.2	11.2	100%	4.49	4.13	0.24
	Non-Dairy Cattle	Mature Females	500	60%	172.9	9.4	30%	3.75	3.45	0.17
		Mature Males	600	60%	152.5	8.3	21%	3.31	3.04	0.17
		Young	230	60%	102.2	5.5	49%	2.22	2.04	0.17
		Avg. Non-Dairy Cattle	391	60%	134.4	7.3	100%	2.91	2.68	0.17
Oceania	Dairy Cattle	Average	500	60%	174.1	9.4	100%	3.77	3.47	0.24
	Non-Dairy Cattle	Mature Females	400	55%	160.5	8.7	52%	3.91	3.60	0.17
		Mature Males	450	55%	138.8	7.5	10%	3.38	3.11	0.17
		Young	200	55%	98.6	5.3	38%	2.41	2.21	0.17
		Avg. Non-Dairy Cattle	330	55%	134.9	7.3	100%	3.29	3.03	0.17

Continued on next page.

TABLE B-1 (CONTINUED)
FEED INTAKE AND MANURE PRODUCTION FOR CATTLE

Region	Livestock Category	Sub-Population	Mass (kg)	Feed Digest. (%)	Energy Intake (MJ/day)	Feed Intake (kg/day)	Pct of Category Population	Manure (kg/h/d dm)	VS (kg/h/d)	Bo (m^3 CH4/kg VS)
Latin America	Dairy Cattle	Average	400	60%	145.9	7.9	100%	3.16	2.91	0.13
	Non-Dairy Cattle	Mature Females	400	60%	148.0	8.0	37%	3.21	2.95	0.10
		Mature Males	450	60%	144.0	7.8	5%	3.12	2.87	0.10
		Young	230	60%	107.5	5.8	58%	2.33	2.14	0.10
		Avg. Non-Dairy Cattle	305	60%	124.4	6.7	100%	2.70	2.48	0.10
Africa & Middle East	Dairy Cattle	Average	275	60%	92.8	5.0	100%	2.01	1.85	0.13
	Non-Dairy Cattle	Mature Females	200	55%	73.2	4.0	13%	1.79	1.64	0.10
		Mature Males Draft	275	55%	93.2	5.1	13%	2.27	2.09	0.10
		Mature Females Grazing	200	55%	93.6	5.1	5%	2.28	2.10	0.10
		Mature Males Grazing	275	55%	112.3	6.1	25%	2.74	2.52	0.10
		Young	75	60%	36.2	2.0	44%	0.78	0.72	0.10
		Avg. Non-Dairy Cattle	173	57%	70.6	3.8	100%	1.68	1.54	0.10
Asia	Dairy Cattle	Average	350	60%	141.6	7.7	100%	3.07	2.82	0.13
	Non-Dairy Cattle	Mature Females Farming	325	55%	113.2	6.1	27%	2.76	2.54	0.10
		Mature Females Grazing	300	60%	105.0	5.7	9%	2.28	2.09	0.10
		Mature Males Farming	450	55%	134.9	7.3	24%	3.29	3.03	0.10
		Mature Males Grazing	400	60%	112.5	6.1	8%	2.44	2.24	0.10
		Young	200	60%	79.3	4.3	32%	1.72	1.58	0.10
		Avg. Non-Dairy Cattle	319	57%	106.8	5.8	100%	2.49	2.29	0.10
Indian Subcontinent	Dairy Cattle	Average Dairy Cow	275	55%	117.7	6.4	100%	2.87	2.64	0.13
	Non-Dairy Cattle	Mature Females	125	50%	63.8	3.5	40%	1.73	1.59	0.10
		Mature Males	200	50%	83.7	4.5	10%	2.27	2.09	0.10
		Young	80	50%	43.2	2.3	50%	1.17	1.08	0.10
		Avg. Non-Dairy Cattle	110	50%	55.5	3.0	100%	1.50	1.38	0.10

Ash content estimated at 8%. Cattle characteristics from Gibbs and Johnson (1993).

TABLE B-2
FEED INTAKE AND MANURE PRODUCTION FOR SWINE AND BUFFALO

Region	Livestock Category	Sub-Population	Mass (kg)	Feed Digest. (%)	Energy Intake (MJ/day)	Feed Intake (kg/day)	Pct of Category Population	Manure (kg/h/d dm)	VS (kg/h/d)	Bo (m^3 CH_4/kg VS)
					Swine					
Developing Countries	Swine	Average	28	50%	13.0	0.7	100%	0.35	0.34	0.29
Developed Countries	Swine	Average	82	75%	38.0	2.1	100%	0.51	0.50	0.45
					Buffalo					
Indian Subcontinent[a]	Buffalo	Adult Males	450	55%	134.5	7.3	14%	3.28	3.02	0.10
		Adult Females	350	55%	139.0	7.5	40%	3.39	3.12	0.10
		Young	200	55%	74.0	4.0	46%	1.80	1.66	0.10
		Average	295	55%	108.0	5.9	100%	2.65	2.43	0.10
Rest of World[b]	Buffalo	Adult Males	450	55%	134.5	7.3	45%	3.28	3.02	0.10
		Adult Females	350	55%	114.0	6.2	45%	2.78	2.56	0.10
		Young	200	55%	74.0	4.1	10%	1.80	1.66	0.10
		Average	380	55%	119.0	6.5	100%	2.91	2.68	0.10

[a] Estimates based on data for India.

[b] Estimates based on data for China.

Ash content taken as 8% for buffalo and 2% and 4% for swine in developed and developing countries, respectively.

Sources: Buffalo characteristics from Gibbs and Johnson (1993). Swine feed intake estimates from Crutzen et al. (1986).

TABLE B-3
MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR DAIRY CATTLE

Climate				Manure Management System MCFs								
				Lagoon	Liquid/ Slurry	Solid Storage	Drylot	Pasture/ Range	Daily Spread	Digester	Burned for Fuel	Other
Cool				90%	10%	1%	1%	1%	0.1%	10%	10%	1%
Temperate				90%	35%	1.5%	1.5%	1.5%	0.5%	10%	10%	1%
Warm				90%	65%	2%	5%	2%	1%	10%	10%	1%
Region	Dairy Cattle Characteristics			Manure Management System Usage (MS%)								
	Mass[a] (kg)	Bo (m^3 CH4 /kg VS)	VS[b] (kg/hd/day)									
North America	600	0.24	5.2	10%	23%	18%	5%	0%	37%	0%	0%	7%
Western Europe	550	0.24	5.1	0%	40%	18%	0%	19%	20%	0%	2%	1%
Eastern Europe	550	0.24	4.1	0%	18%	68%	0%	13%	1%	0%	0%	0%
Oceania	500	0.24	3.5	16%	1%	0%	0%	76%	8%	0%	0%	0%
Latin America	400	0.13	2.9	0%	1%	1%	0%	36%	62%	0%	0%	0%
Africa	275	0.13	1.9	0%	0%	1%	0%	83%	5%	0%	6%	4%
Middle East	275	0.13	1.9	0%	1%	2%	0%	80%	2%	0%	17%	0%
Asia	350	0.13	2.8	4%	38%	0%	0%	20%	29%	2%	7%	0%
Indian Subcon.	275	0.13	2.6	0%	1%	0%	0%	27%	19%	1%	51%	0%

[a] Average dairy cow mass for each region.

[b] Average VS production for per head per day for the average dairy cow.

Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \times VS \times 365 \times \sum_{i=1}^{\text{all manure systems}} MS\%_i \times MCF_{ik}$$

Emission Factors kg CH_4 / hd / yr		
Cool	Temperate	Warm
36	54	76
14	44	81
6	19	33
31	32	33
0	1	2
1	1	1
1	2	2
7	16	27
5	5	6

TABLE B-4

MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR NON-DAIRY CATTLE

Climate	Manure Management System MCFs								
	Lagoon	Liquid / Slurry	Solid Storage	Drylot	Pasture / Range	Daily Spread	Digester	Burned for Fuel	Other
Cool	90%	10%	1%	1%	1%	0.1%	10%	10%	1%
Temperate	90%	35%	1.5%	1.5%	1.5%	0.5%	10%	10%	1%
Warm	90%	65%	2%	5%	2%	1%	10%	10%	1%

Region	Non-Dairy Cattle Characteristics			Manure Management System Usage (MS%)									Emission Factors kg CH_4 / hd / yr		
	Mass[a] (kg)	B_o (m^3 CH4 /kg VS)	VS[b] (kg/hd/day)	Lagoon	Liquid / Slurry	Solid Storage	Drylot	Pasture / Range	Daily Spread	Digester	Burned for Fuel	Other	Cool	Temperate	Warm
North America	357	0.17	2.4	0%	1%	0%	14%	84%	0%	0%	0%	1%	1	2	3
Western Europe	405	0.17	2.7	0%	50%	0%	2%	38%	0%	0%	2%	8%	6	20	38
Eastern Europe	391	0.17	2.7	0%	28%	0%	0%	26%	0%	0%	0%	46%	4	13	23
Oceania	330	0.17	3.0	3%	0%	0%	6%	91%	0%	0%	0%	0%	5	6	7
Latin America	305	0.10	2.5	0%	0%	0%	0%	99%	0%	0%	0%	1%	1	1	1
Africa	173	0.10	1.5	0%	0%	0%	1%	95%	1%	0%	3%	0%	0	1	1
Middle East	173	0.10	1.5	0%	0%	0%	1%	79%	2%	0%	17%	2%	1	1	1
Asia	319	0.10	2.3	0%	0%	0%	46%	50%	2%	0%	2%	0%	1	1	2
Indian Subcon	110	0.10	1.4	0%	1%	0%	4%	22%	20%	1%	53%	0%	2	2	2

[a] Average non-dairy cow mass for each region.

[b] Average VS production for per head per day for the average non-dairy animal.

Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \times VS \times 365 \times \sum_{j=1}^{\text{all manure systems}} MS\%_j \times MCF_{jk}$$

Table B-5
Manure Management Emission Factor Derivation for Buffalo

Climate	Manure Management System MCFs						
	Liquid/ Slurry	Drylot	Pasture/ Range	Daily Spread	Digester	Burned for Fuel	Other
Cool	10.0%	1.0%	1.0%	0.1%	10.0%	10.0%	1.0%
Temperate	35.0%	1.5%	1.5%	0.5%	10.0%	10.0%	1.0%
Warm	65.0%	5.0%	2.0%	1.0%	10.0%	10.0%	1.0%

Region	Buffalo Characteristics			Manure Management System Usage (MS%)							Emission Factors kg CH4 / hd / yr		
	Mass[a] kg	Bo m³ CH4 /kg VS	VS[b] kg/hd/day	Liquid/ Slurry	Drylot	Pasture/ Range	Daily Spread	Digester	Burned for Fuel	Other	Cool	Temperate	Warm
North America	(not applicable)												
Western Europe	380	0.10	3.9	20%	79%	0%	0%	0%	0%	0%	3	8	17
Eastern Europe	380	0.10	3.9	24%	0%	29%	0%	0%	0%	47%	3	9	16
Oceania	(not applicable)												
Latin America	380	0.10	3.9	0%	0%	99%	0%	0%	0%	1%	1	1	2
Africa	(not applicable)												
Middle East	380	0.10	3.9	0%	0%	20%	19%	0%	42%	19%	4	5	5
Asia	380	0.10	3.9	0%	41%	50%	4%	0%	5%	0%	1	2	3
Indian Subcon.	295	0.10	3.1	0%	4%	19%	21%	1%	55%	0%	4	5	5

[a] Average buffalo mass for each region.

[b] Average VS production for per head per day for the average buffalo.

Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \times VS \times 365 \times \sum_{j=1}^{\text{all manure systems}} MS\%_j \times MCF_{jk}$$

TABLE B-6
MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR SWINE

Climate	Lagoon	Liquid/ Slurry	Solid Storage	Drylot	Pit <1 month	Pit >1 month	Daily Spread	Digester	Other
	Manure Management Systems MCFs								
Cool	90%	10%	1%	1%	5%	10%	0.1%	10%	1%
Temperate	90%	35%	1.5%	1.5%	18%	35%	0.5%	10%	1%
Warm	90%	65%	2%	5%	33%	65%	1%	10%	1%

Region	Swine Characteristics			Manure Management System Usage (MS%)									Emission Factors kg CH4 / hd / yr		
	Mass[a] kg	B_O m³ CH4 /kg VS	VS[b] kg/hd/day	Lagoon	Liquid/ Slurry	Solid Storage	Drylot	Pit <1 month	Pit >1 month	Daily Spread	Digester	Other	Cool	Temperate	Warm
North America	82	0.45	0.5	24%	1%	2%	16%	10%	26%	0%	0%	19%	10	14	18
Western Europe	82	0.45	0.5	0%	0%	21%	2%	3%	73%	0%	0%	1%	3	10	19
Eastern Europe	82	0.45	0.5	8%	0%	39%	14%	19%	19%	0%	0%	1%	4	7	11
Oceania	82	0.45	0.5	54%	0%	3%	15%	0%	0%	0%	0%	28%	20	20	20
Latin America	28	0.29	0.3	0%	8%	10%	41%	0%	0%	2%	0%	40%	0	1	2
Africa	28	0.29	0.3	0%	6%	6%	87%	1%	0%	0%	0%	0%	0	1	2
Middle East	28	0.29	0.3	0%	14%	0%	69%	0%	17%	0%	0%	0%	1	3	6
Asia	28	0.29	0.3	0%	40%	0%	54%	0%	0%	0%	7%	0%	1	4	7
Indian Subcon.	28	0.29	0.3	9%	22%	16%	30%	3%	0%	9%	8%	3%	3	4	6

[a] Average swine mass for each region.

[b] Average VS production for per head per day for the average swine.

Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \times VS \times 365 \times \sum_{j=1}^{\text{all manure systems}} MS\%_j \times MCF_{jk}$$

TABLE B-7
MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR OTHER LIVESTOCK

Animal		Animal Characteristics						Manure Management System MCFs[a]			Emission Factors[a] kg CH4 / hd / yr		
		Mass (kg)	Digest (%)	Intake/d (kg Feed)	% Ash (Dry Basis)	VS/day (kg VS)	B_o (m^3/kg VS)	MCF Cool	MCF Temperate	MCF Warm	Cool	Temperate	Warm
Sheep	**Developed Countries**	43	60%	1.08	8.0	0.40	0.19	1%	1.5%	2%	0.19	0.28	0.37
	Developing Countries	28	50%	0.70	8.0	0.32	0.13	1%	1.5%	2%	0.10	0.16	0.21
Goats	Developed Countries	30	60%	0.76	8.0	0.28	0.17	1%	1.5%	2%	0.12	0.18	0.23
	Developing Countries	30	50%	0.76	8.0	0.35	0.13	1%	1.5%	2%	0.11	0.17	0.22
Camels	Developed Countries	217	50%	5.42	8.0	2.49	0.26	1%	1.5%	2%	1.59	2.38	3.17
	Developing Countries	217	50%	5.42	8.0	2.49	0.21	1%	1.5%	2%	1.28	1.92	2.56
Horses	Developed Countries	238	70%	5.96	4.0	1.72	0.33	1%	1.5%	2%	1.39	2.08	2.77
	Developing Countries	238	70%	5.96	4.0	1.72	0.26	1%	1.5%	2%	1.09	1.64	2.18
Mule/Asses	Developed Countries	130	70%	3.25	4.0	0.94	0.33	1%	1.5%	2%	0.76	1.14	1.51
	Developing Countries	130	70%	3.25	4.0	0.94	0.26	1%	1.5%	2%	0.60	0.90	1.19
Poultry[b]	Developed Countries	1.1	NR[c]	NR	NR	0.10	0.32	1%	1.5%	2%	0.078	0.117	0.157
	Developing Countries	NR	NR	NR	NR	0.02	0.24	1%	1.5%	2%	0.012	0.018	0.023

[a] The range of estimates reflects cool to warm climates. Cool climates have an average annual temperature below 15°C; temperate climates have an average annual temperature between 15°C and 25°C; and warm climates have an average annual temperature above 25°C.

[b] Poultry include chickens, ducks, and turkeys.

[c] Not reported.

Sources: Except for poultry, emission factors were developed from: feed intake values and feed digestibilities used to develop the enteric fermentation emission factors (see Appendix A); MCF, and B_o values reported in Woodbury and Hashimoto (1993). All manure is assumed to be managed in dry systems, which is consistent with the manure management system usage reported in Woodbury and Hashimoto (1993). Emission factors for poultry are based on Safley et al. (1992) and Woodbury and Hashimoto (1993).

Appendix C

Derivation of Tier 2 Enteric Fermentation Equations

This appendix summarises the derivation of the relationship between net energy (NE) and digestible energy (DE) that is used to estimate total feed-intake requirements for cattle. This derivation is drawn from Gibbs and Johnson (1993).

As described in the main text, the relationship among the energy values of feed consumed by cattle can be summarised as follows:

Digestible Energy = Gross Energy - Faecal Losses

Metabolisable Energy = Digestible Energy - Urinary and Combustible Gas Losses

Net Energy = Metabolisable Energy - Heat Increment

Net Energy = Gross Energy - Faecal Losses - Urinary and Combustible Gas Losses - Heat Increment

NRC (1984) presents the following quantitative relationships among these energy values:

$$ME = 0.82 \times DE \qquad (C.1)$$

$$NE_m = (1.37 \times ME) - (0.138 \times ME^2) + (0.0105 \times ME^3) - 1.12 \qquad (C.2)$$

$$NE_g = (1.42 \times ME) - (0.174 \times ME^2) + (0.0122 \times ME^3) - 1.65 \qquad (C.3)$$

where:

DE = digestible energy in Mcal/kg (dry matter basis);

ME = metabolisable energy in Mcal/kg (dry matter basis);

NE_m = net energy for maintenance in Mcal/kg (dry matter basis); and

NE_g = net energy for growth in Mcal/kg (dry matter basis).

Using these relationships, the ratio of NE_m and NE_g to ME or DE can be derived as follows:

$$NE/DE = 1.123 - (4.092 \times 10^{-3} \times DE\%) + (1.126 \times 10^{-5} \times (DE\%)^2) - 25.4/DE\% \qquad (C.4)$$

$$NE_g/DE = 1.164 - (5.160 \times 10^{-3} \times DE\%) + (1.308 \times 10^{-5} \times (DE\%)^2) - 37.4/DE\% \qquad (C.5)$$

where:

NE/DE = the ratio of net energy consumed for maintenance, lactation, work and pregnancy to digestible energy consumed;

NE_g/DE = the ratio of net energy consumed for growth to digestible energy consumed; and

DE% = digestible energy as percentage of gross energy, expressed in per cent (e.g., 65%).

Graph C-1 shows the relationships in graphical form. As shown in the graph, the ratio of NE to DE is non-linear, with an increasing slope with decreasing DE. These relationships imply that at lower values of DE, cattle are able to recover a decreasing portion of the energy to use for maintenance or growth.

For the purpose of estimating methane emissions from cattle, applying these relationships to cattle consuming relatively low-quality feeds (such as cattle in many tropical countries) may be inappropriate because the relationships were developed based on analyses of the higher-quality feeds typically found in the United States temperate agriculture system. Consequently, the experimental basis for extrapolating the non-linear relationships to low levels of DE is not very strong.

In examining other energy systems, it is seen that they also indicate that the rate of net energy retention declines at lower values of digestible energy. Unlike the NRC system, however, many imply a *linear* relationship between NE and DE. The UK energy system (ARC, 1980), which is typical of the energy systems used in Europe, has a slope for the linear NE_m:DE relationship that is similar to the slope of the non-linear NRC relationship in the range of 65 per cent-70 per cent digestibility. Similarly, the slope of the UK NE_g:DE relationship is similar to the slope of the non-linear NRC relationship in the range of 60-65 per cent digestibility.

To avoid possible biases in estimating feed-intake requirements in this study, the relationships were extrapolated linearly for DE values below 65 per cent using the average slopes of the NRC relationships between 60 and 70 per cent DE. The derived equations are as follows:

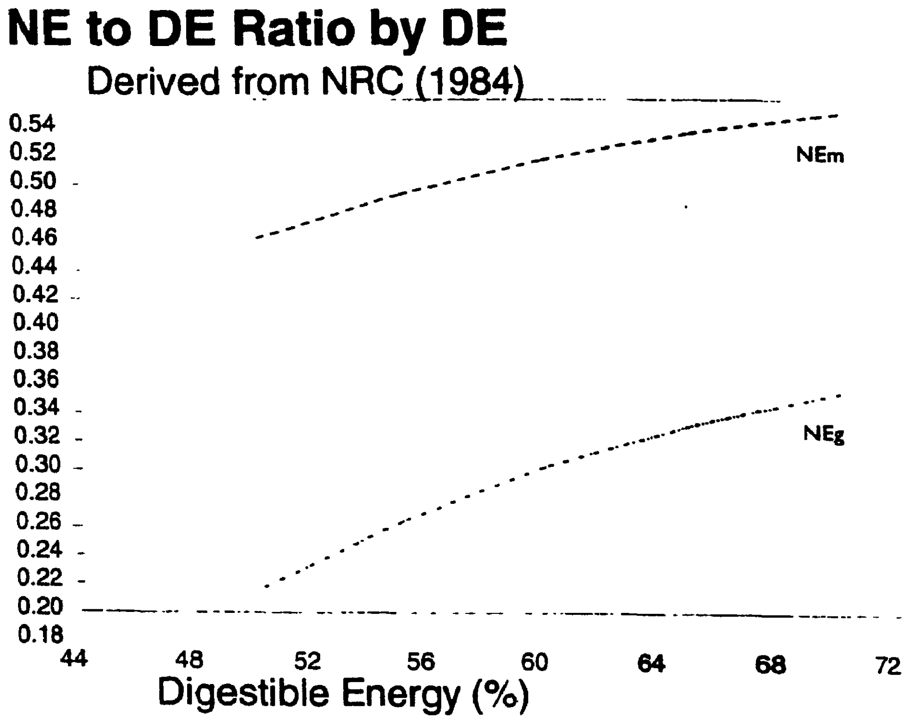
$$NE/DE = 0.298 + 0.00335 \times DE\% \quad (C.6)$$

$$NE_g/DE = -0.036 + 0.00535 \times DE\% \quad (C.7)$$

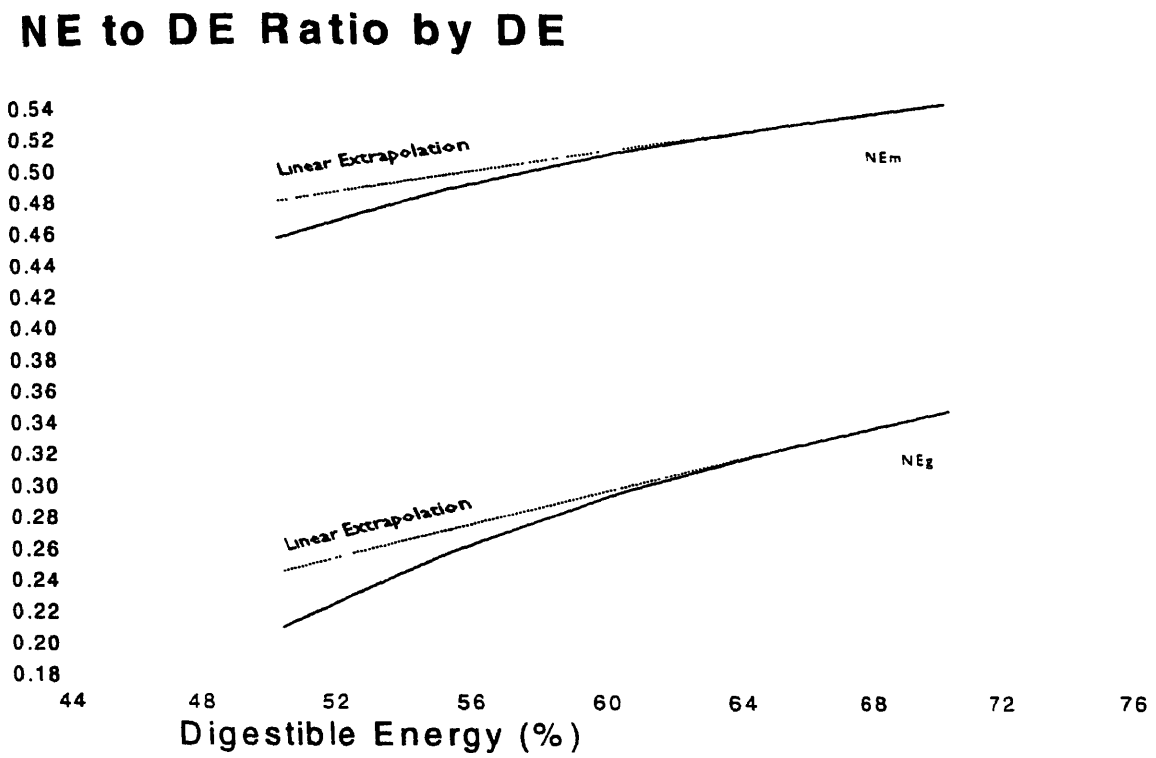
Graph C-2 shows the extrapolated linear relationships along with the non-linear estimates. As expected, the linear extrapolations fall *above* the original non-linear estimates.

The implication of making this adjustment to the NRC (1984) relationship for the global emissions estimate is relatively minor. Gibbs and Johnson (1993) report that using the non-linear relationship to estimate global emissions from cattle increases the 1990 emissions estimate by 1000 Gg, from 58,100 Gg to 59,100 Gg. Considering the wide range of factors that contribute to uncertainty in the estimates, including characterisation of animal populations, this adjustment has a minor influence on the estimates.

Graph C-1: NRC NE:DE Relationship



Graph C-2: Linear Extrapolation Of The NRC NE:DE Relationship



4.3 Methane Emissions from Rice Cultivation: Flooded Rice Fields

4.3.1 Overview

Anaerobic decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes to the atmosphere primarily by diffusive transport through the rice plants during the growing season. Upland rice fields, which are not flooded and therefore do not produce significant quantities of CH_4, account for approximately 10 per cent of the global rice production and about 15 per cent of the global rice area under cultivation. The remaining area is wetland rice, consisting of irrigated, rainfed, and deepwater rice. The global wetland rice area harvested annually in the early 1980s was about 123.2 million hectares, over 90 per cent of which was in Asia (Neue et al., 1990).[14]

Of the wide variety of sources for the atmospheric CH_4, rice paddy fields are considered one of the most important sources. The Intergovernmental Panel on Climate Change (Watson *et al.* 1992) estimated the global emission rate from paddy fields at 60 Tg/yr, with a range of 20 to 150 Tg/yr.. This is about 5-30 per cent of the total emission from all sources. This figure is mainly based on field measurements of CH_4 fluxes from paddy fields in the United States, Spain, Italy, China, India, Australia and Japan.

The measurements at various locations of the world show that there are large temporal variations of CH_4 fluxes and that the flux differs markedly with soil type, application of organic matter and mineral fertiliser. The wide variations in CH_4 fluxes also indicate that the flux is critically dependent upon several factors including climate, characteristics of soils and paddy, and agricultural practices. On the other hand, about 90 per cent of the world's harvested area of rice fields is located in Asia. Of the total harvested area in Asia, about 60 per cent is located in India and China.

Methane production processes

The major pathways of CH_4 production in flooded soils are the reduction of CO_2 with H_2, with fatty acids or alcohols as hydrogen donor, and the transmethylation of ethanoic acid or methanol by methane-producing bacteria (Takai 1970; Conrad 1989). In paddy fields, the kinetics of the reduction processes are strongly affected by the composition and texture of soil and its content of inorganic electron acceptors. The period between flooding of the soil and the onset of methanogenesis can apparently be different for the various soils. However, it is unclear if soil type also affects the rates of methanogenesis and CH_4 emission when steady state conditions have been reached (Conrad 1989).

The redox[15] potential is the most important factor for production of CH_4 in soils. The Eh, or electron activity, of the soil gradually decreases after flooding. This is due to a decrease in the activity of the oxidised phase and increased activity of the reduced phase. Takai *et al.* (1956) demonstrated that the redox potential of a soil must be below -200 mV in order to have CH_4 production. Yamane and Sato (1964) also showed that the evolution of CH_4 from flooded paddy soils did not commence until the Eh fell below -200 mV. There is a correlation between the soil redox potential and methane emission (Patrick *et al.* 1981; Cicerone *et al.* 1983; Yagi and Minami 1990).

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[14] The term "harvested area" has a different meaning than "cultivated area" in that the former accounts for double and triple cropping. For example, if a country has 10 million hectares of land under rice cultivation, all of which are double-cropped (i.e., two crops of rice are grown on each hectare each year), then this country has 20 million hectares of rice area harvested annually.

[15] Redox refers to oxidation-reduction, two processes that take place simultaneously. Oxidation is the loss of an electron by an atom, and reduction is the gain of an electron by an atom.

Substrate and nutrient availability is also an important factor. Application of rice straw to paddy fields significantly increases the CH_4 emission rate compared with application of compost prepared from rice straw or chemical fertiliser.

Soil temperature is known to be an important factor in affecting the activity of soil micro-organisms. This is to a certain extent related to the soil moisture content because both the heat capacity and the heat conductivity are lower for a dry soil than for a wet soil. Yamane and Sato (1961) have already found that CH_4 formation reached a maximum at 40 °C in waterlogged alluvial soils. CH_4 formation decreased above 40°C, and stopped at 60° C. The rate of methane formation was very small below 20°C.

It is generally recognised that CH_4 formation is only efficient in a very narrow range around neutrality (pH from 6.4 to 7.8). The effect of flooding is to increase the pH in acid soil, while it decreases the pH in alkaline soil. The increase of pH in acid soils is mainly due to the reduction of acidic Fe^{3+} to Fe^{2+}.

The act of growing plants on soils may also affect the emission of gaseous CH_4. At later growth stages of rice, more nitrogen gas and less CH_4 were found in wetlands soils planted to rice than in an unplanted rice field (Yoshida 1978). Yamane and Sato (1963) found that flooded soils planted with rice frequently evolve less CH_4 than the corresponding uncultivated sites. The addition of sulphate as chemical fertiliser to flooded soils also influences the production of CH_4 because of its effect on raising the redox potential and of the toxic effect of its reduction product. Also, the addition of sulphate increases the activities of sulphate-reducing bacteria, which outcompete methanogens for the substrate. CH_4 will not be formed in paddy soils until all the sulphate has been reduced (Takai 1980).

The addition of nitrate as chemical fertiliser to flooded soils may also suppress the production of CH_4, because nitrate acts as a terminal electron acceptor in the absence of molecular oxygen during anaerobic respiration, and poises the redox potential of soils at values such that the activity of strict anaerobes is prevented.

There are three processes of CH_4 release into the atmosphere from rice fields. Methane loss as bubbles from paddy soils is a common and significant mechanism. Diffusion loss of CH_4 across the water surface is another process. The third is CH_4 transport through rice plants, which has been reported as the most important phenomenon (Seiler *et al.* 1984; Cicerone *et al.* 1983; Minami and Yagi 1988; Nouchi *et al.* 1990).

Many researchers reported that more than 90 per cent of the total CH_4 produced by rice fields is released by diffusive transport through the aerenchym system of the rice plants and not by diffusion or escape of bubbles across the air-water interface. Emission through plants may be expected to show great seasonal variations tied to environmental changes in soil conditions and variations in plant growth stage, respiration and photosynthesis rates.

Although CH_4 flux rates are revealed to be a function of the total amount of CH_4 in the soil, there is a possibility that the gas may be consumed in the thin oxidised layer close to the soil surface and in deep flooding water. It is known that soil methanogenic bacteria can grow with CH_4 as their sole energy source, and other soil bacteria, *Nitrosomonas* species consume CH_4 (Seiler and Conrad 1987). Methane is also leached to ground water, as a small part dissolves in water. Therefore a reduction in soil methane does not necessarily mean that all this CH_4 has been emitted into the atmosphere.

Global emissions from rice fields

The area harvested of paddy rice has increased from 86 Mha in 1935 to 144 Mha in 1985, which means an annual average increase of 1.05 per cent. The average annual increase was 1.23 per cent between 1959 and 1985. However, in the last few years, the rate of expansion of the total paddy acreage has decreased (Minami, 1993).

About 90 per cent of the world's harvested area of rice fields is located in Asia. Of the total harvested area in Asia, about 60 per cent is located in India and China. Table 4-9 provides a summary of measured emissions at a number of specific research sites around the world. It should be noted that methane fluxes from paddy rice fields vary substantially from day to day, and at different times during a day (e.g., day and night). The data presented here are based on frequent measurements which capture the diurnal variations, and variations over the growing season. Based on area and production statistics, with average emission values, a number of researchers have estimated global emissions from rice.

TABLE 4-9
METHANE EMISSION FROM RICE PADDY FIELDS IN VARIOUS LOCATIONS OF THE WORLD

Location	Daily average (g/m^2 day)	Flooding period (days)	Season total (g/m^2)	Literature
China (Hangzhou)				Wang et al. (1989)
Early rice	0 19	75-95	14-18	
Late rice	0.69	80-140	55-97	
Single rice	0.44	120-150	53-66	
China (Tuzu)	1.39	120	167	Khalil et al. (1991)
India	0.04-0.46	60	2-28	Parashar et al. (1991)
Italy	0.10-0.68	130	12-77	Schutz et al. (1989)
Japan				Yagi & Minami (1990, 92)
Ryugasaki (Peat soil)	0.39	115	45	
Ryugasaki (Gley soil)	0.07-0.37	110	8-43	
Tsukuba (Andosol)	<0.01-0.10	130	<1-13	
Spain	0.10	120	12	Seiler et al. (1984)
Thailand				Yagi et al. (1992)
Suphan Buri	0.47-0.77	97-109	51-75	
Khlong Luang	0.09	83	7	
Chai Nat	0.04	94	4	
USA				
California	0.25	100	25	Cicerone et al. (1983)
Texas	0 05-0 36	84-85	5-31	Sass et al. (1990, 91)
Louisiana	0.27-0.48	77	21-37	Lindau et al. (1991)

Global emissions of CH_4 from rice paddies reported by several researchers are summarised in Table 4-10. Extrapolation of emission rates to a global scale is very difficult, because the effects of variations in agricultural practices, number of crops per year, soil types and other factors discussed above are uncertain.

The IPCC (Watson et al. 1990) presented a candidate list of CH_4 sources to the atmosphere as annual release rates. The total annual source is constrained to be 525 Tg CH_4/yr. Rice paddies are listed as a source of 110 Tg CH_4 with a factor of 7 width in the likely range from 25 to 170 Tg CH_4/yr.

More recently, the IPCC (Watson et al., 1992) estimated rice paddy emissions to be 60 Tg CH_4/yr with the range of 20 to 150 Tg CH_4/yr. These are the most reasonable data at this moment.

TABLE 4-10

GLOBAL ANNUAL METHANE EMISSION FROM RICE FIELDS AS ESTIMATED BY DIFFERENT AUTHORS

Reference	Estimate (Tg CH_4 y^{-1})
Koyama (1964)	190
Ehhalt and Schmidt (1978)	280
Cicerone and Shetter (1981)	59
Khalil and Rasmussen (1983)	95
Seiler et al (1984)	35- 59
Blake (1984)	142-190
Crutzen (1985)	120-200
Holzapfel-Pschorn and Seiler (1986)	70-170
Cicerone and Oremland (1988)	60-170
Schutz et al. (1989)	50-150
Aselman and Crutzen (1989)	60-140
Schutz and Seiler (1989)	70-170
Wang et al. (1990)	60-120
Neue et al. (1990)	25- 60
Bouwman (1990)	53-114
Yagi and Minami (1990)	22- 73
IPCC (1990)	25-170
IPCC (1992)	20-150
Minami and Yagi (1993)	12-113

4.3.2 Methods For Estimating Emissions[16]

Emissions of methane from rice fields can be represented as follows:

$$F_c = \sigma_{comp} \times E \tag{1}$$

where:

- F_c is the estimated emission of methane from a country (c) in Tg/yr.
- σ_{comp} is the "composite emission factor" (Tg/hectare-day) representative of the conditions in a country, and
- E is the "extrapolant" (hectare-days/yr).

The composite emission factor is evaluated from direct field measurements of methane fluxes, and the extrapolant consists of the product of the rice area harvested per year and the fraction of the year the fields are used for growing rice (season length):

$$E = A \text{ (hectares/yr)} \times T \text{ (days)}$$

The extrapolant is obtained from geographical and agricultural archives.

In practice, it may be more efficient to calculate the total annual emissions from a country as a sum of the emissions over a number of conditions. Total rice production can be divided into subcategories based on different biological, chemical and physical factors that control methane emissions from rice fields. In large countries, this may include different geographic regions. This approach to emissions estimation can be represented as follows:

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[16] From Khalil, 1993, reporting recommendations of the expert group.

$$F_c = \sum_i \sum_j \cdots \sum_k \phi_{ijk} \cdots A_{ijk} \cdots T_{ijk} \qquad (2)$$

where:

- ijk... are categories under which methane emissions from rice fields may vary.

For instance, i may represent water levels in the rice fields such as fields inundated for the duration of the growing season (flooded regime) or fields under water only intermittently, either from managed irrigation when water is not readily available or when rains do not maintain flooded conditions throughout the growing season (intermittent regime) or highland rice when the fields are seldom flooded during the growing season (dry regime). j may represent fertilisation regimes under each of the conditions represented by the index i, and so on. As more factors are identified, more categories need to be included. Inclusion of additional factors does not, however, lead to an automatic improvement of the total emissions since errors propagate and may create large uncertainties. However, using extremely simplified methods for calculating the representative flux (ϕ_{comp}) also may lead to substantial errors.

From field experiments it is apparent that methane emissions from rice fields are affected by many factors. The working group focused on the factors for which there was sufficient information on both the emission factors and the extrapolants. Including the available information in the present estimates of country-by-country emissions may improve the accuracy, but at present it is not certain which factors have the greatest effect on emissions.

The factors clearly identified by field experiments are 1) water level and its history in the growing season, 2) temperature, 3) fertiliser applications, 4) soil type, 5) cultivar, and 6) agricultural practices such as direct seeding or transplanting. Data show that higher temperatures, continuously flooded fields, some types of organic fertilisers and certain cultivars lead to higher emissions compared to rice grown at lower temperatures, with intermittent or managed irrigation in which the fields are not continuously inundated and where chemical fertilisers are used.

At present there are insufficient data to incorporate most of these factors. Nonetheless, the estimates can be improved substantially by incorporating the current knowledge on the first two factors, namely water levels and temperature. For some countries the effects of organic and mineral fertiliser can be included. Inclusion of the remaining factors may be feasible within 1-2 years.

4.3.3 Summary Of Recommended Method

Basic Method

Data on rice cultivation under different water management techniques should be available from most of the important rice-producing countries. Therefore, the basic method for estimating emissions from each country includes estimates for the three water regimes, namely:

- flooded; fields inundated for the duration of the growing season,

- intermittently flooded: fields not inundated for the duration of the growing season and.
- dry (or upland): fields seldom flooded during the growing season. However, emissions from dry rice fields are not significant, and are thus not included in the calculation.

In addition, considerable data exist to support the development of temperature-adjusted emission coefficients. Therefore, the basic method accounts for water management regime and temperature.

The discussion refers to a single inventory (or base) year, (e.g., 1990) but an average over three years around the base year (e.g., 1989-1991) is recommended if possible. For the inventory year, a number of input data are required.

- Area of rice cultivation by water management regime in megahectares (Mha). As discussed above, this includes hectares counted twice if two crops are grown.
- Season length. For the purposes of this methodology, this is defined as the average (for the country or subcategory) length of time in days, from seeding or transplanting until harvest.
- Emission factors for flooded and intermittently flooded conditions, adjusted for average temperature.

Calculate the Flux for each water management category as follows:

1 Multiply area (Mha) by season length (days) to obtain the extrapolant (Mha-days).

2 Multiply Mha-days by the appropriate emission factor (kg/ha-day) based on average temperature and water management regime.

The result is methane emissions (Gg) for each category. The total flux for the country is the sum of the individual results for each category.

Default data

In many cases, especially at the beginning of the process, there will be important rice-growing areas for which specific fluxes or details of extrapolants will not be available. In such cases the regional and country-specific default data provided in Tables 4-11 and 4-12 can be used to carry out first order estimates. These data may also be used by national experts for comparison and checking of locally developed values. Several ongoing activities to improve comparable measurement data have been identified. These include work being carried out at the International Rice Research Institute (IRRI, 1994), Neue and Sass (1994) and by the IGBP-START Regional Research Networks. Experts may contact the START Regional Networks directly:

TEACOM Regional Research Network (China)
Laboratory of Climate Research
Institute of Atmospheric Physics
Chinese Academy of Sciences
P.O. Box 2718, Zhongguancan
Beijing 100080, China
TEL/FAX: (+86-1) 256-2458
e-mail: fucb @ bepc 2.thep.ac.cn

SARCS Regional Research Network (South East Asia)
Institute of Environmental Research
Chulalongkom University in Bangkok
Bangkhen, Bangkok 10330, Thailand
TEL: (+66-2) 251-4426 / 7
FAX: (+66-2) 251-4804

SASCOM Regional Research Network (Southern Asia)
National Physical Laboratory
Hillside Road, New Delhi-110012, India
TEL: (+91-11) 574-5298
FAX: (+91-11) 575-2678
e-mail (Internet): apmitra @ doe.ernet.in

Area Statistics

In Table 4-11, the area information is based on statistics from the FAO Yearbook (UN, 1992), China Agricultural Yearbook (1990) and World Rice Statistics (IRRI, 1990). Shallow rainfed rice was used as a proxy for intermittently flooded rice fields, and where data on irrigation practices are not available, those hectares are to be taken as the flooded regime. Allocation of areas to categories, e.g., dryland rice and shallow rainfed rice were based on the work of IRRI (1990), Huke (1982) and Grist (1986). Details of the development of these default data are in Shearer and Khalil (1993).

Season Length

Values provided for season length in Table 4-11 are adapted from the crop calendars of Matthews et al. (1991)[17]. The original crop calendars provide estimates of the months and parts of months in which rice crops are grown in a particular country or region. This includes some staggered planting and harvesting of crops. Thus, the average season length is generally less than the value taken directly from the crop calendars. Using the length of the season calculated directly from the crop calendar in the basic method would lead to an overestimate of the methane emission season. The crop calendar values from Matthews et al. tables were reduced by 10 to 45 days to obtain season length as defined here. In Table 4-11, "Season Length" is the weighted average of all growing seasons after they have been adjusted for the crop calendar length.

Emission Factors

Table 4-12 provides default emission factors for intermittently flooded and flooded rice fields. Emissions from dryland rice are assumed to be 0 and ignored in the emission calculations.

> For continuously flooded rice, a "modal" average seasonal flux for Asian countries was estimated to be 0.47 (±0.12) g/m^2/day (equivalent to 20 (±5) mg/m^2/hour, or 4.7 kg/ha/day), with a base temperature of 23°C. The base temperature is representative of average seasonal temperatures in the areas of Asia where flux measurements are available (20-25°C). These flux values are representative of flooded rice fields where organic fertiliser is used, which is common in rice-growing countries where measurements are not available.
>
> For intermittently flooded rice, a simple correction was applied based on the work of Chen et al. (1993) and Sass et al. (1992). Fluxes were assumed to be 60 per cent of those from flooded rice fields. Currently, there is very little measurement data

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[17] These crop calendars are also reproduced in OECD (1991)

available for emissions from intermittently flooded rice. The current estimating procedure may underestimate the flux of methane from this category, since it assumes that there is one drought episode in every crop of shallow rainfed rice fields world-wide. On the other hand, limited recent measurements from intermittently flooded (irrigated) test plots in India (Parashar, 1994) indicate that emission rates may be only about 10 per cent of those from continuously flooded areas.

Temperature corrections were made using the base temperature emission factor and:

$$\text{multiplying by} \quad [Q_{10}]^{T-T_b/10\,C}$$

with a base temperature of 23°C and $Q_{10} = 1.8$, where Q_{10} is the ratio of the flux at temperature 10°C above the base temperature.

Default values in Table 4-12 can be used for initial calculation where local measurements are not adequate. However, national experts are encouraged to substitute locally available data for default values if available. If this is done it is important to ensure that these coefficients are based on a sufficient number of measurements to capture the variability and produce a representative seasonal average value, which is needed for inventory calculations.

Possible Refinements

National experts are encouraged to go beyond the basic method, and to add as much detail as can be scientifically justified, based on laboratory and field experiments and theoretical calculations, to arrive at the estimate of emissions from rice cultivation in their country. These details should be incorporated into subcategories (indices j, k ,... in Equation 2) under each of the three main water management categories in Equation 2 so that they can be compared at that level with data from other countries.

For example:

Where data are available on fertiliser type, it may be incorporated into the calculations. Each category, (e.g., continuously flooded) would be further divided into as follows:

Flux (flooded) = Flux (fooded|organic) + Flux (flooded|chemical)

Then the organically fertilised subcategory would be calculated separately as described above using the emission factors, areas, season length, and temperatures applicable to the amount of rice grown under flooded conditions using organic fertilisers.

This procedure would then be repeated for as many separate subcategories as have been defined. Each additional factor may be incorporated in the same manner by further subdividing each category. In all cases the results should be summed to provide subtotals for the primary categories identified in the basic method.

The procedure is described by the following general formulae:

$$\text{Base:} \quad F = \sum_i \phi_i A_i T_i \tag{3}$$

where i represents water management regimes – flooded, intermittently flooded, dry.

Adding fertiliser effect:

$$\phi_i A_i T_i = \sum_j \phi_{ij} A_{ij} T_{ij} \qquad (4)$$

where j represents different fertiliser types. Each component of (3) is calculated by (4).

Additional factors: soil type, for example:

$$\varphi_{ij} A_{ij} T_{ij} = \sum_k \phi_{ijk} A_{ijk} T_{ijk} \qquad (5)$$

where k represents different soil types. Each component of (4) is calculated from (5) and then each component of (3) is calculated from (4).

The process may be continued for more factors.

In all cases, the emission inventory must be fully documented. The documentation has two aspects. First, method of calculation must be specified as in Equation 2. Matrices of emission factors and extrapolants must be delineated. Second, all data and original sources must be referenced, if not included explicitly as part of the inventory report. It is desirable in all cases to rely on published information, whether from the county's government, an international organisation such as the UN-FAO, or the scientific literature.

TABLE 4-11
DEFAULT ACTIVITY DATA - HARVESTED RICE

Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
AMERICAS					
USA	1114	123	100	0	0
Belize	2	139	10	90	0
Costa Rica	53	103	10	90	0
Cuba	150	139	100	0	0
Dominican Rep	93	103	98	2	0
El Salvador	15	123	10	90	0
Guatemala	15	139	10	90	0
Haiti	52	123	40	60	0
Honduras	19	123	10	90	0
Jamaica	0	123	40	60	0
Mexico	123	130	41	59	0
Nicaragua	48	123	10	90	0
Panama	92	103	5	95	0
Puerto Rico	0	123	75	25	0
Trinidad & Tobago	5	103	45	55	0
Argentina	103	121	100	0	0
Bolivia	110	101	25	75	0
Brazil	4450	101	18	76	6
Chile	35	121	79	21	0
Columbia	453	124	53	47	0
Ecuador	266	100	40	10	50
Guyana	68	123	95	5	0
Paraguay	34	101	50	50	0
Peru	185	167	84	16	0
Surinam	58	123	100	0	0
Uruguay	108	138	100	0	0
Venezuela	119	103	90	10	0

Notes. Areas were taken from FAO Yearbook (UN, 1992), China Agricultural Yearbook (1990) and World Rice Statistics (IRRI, 1990)

Season length is an average weighted by area of the adjusted growing season The adjusted growing season uses the crop calendars of Matthews et al., (1991) reduced by 10-45 days. See Shearer and Khalil (1993) for details.

"Continuously Flooded" rice is actually the percentage irrigated. "Dry" is the percentage of dryland or upland rice: "Intermittently Flooded" is actually the percentage of shallow rainfed rice. Sources. DeDatta (1975), Huke, (1982), Grist (1986), IRRI (1990)

TABLE 4-11 (CONTINUED)
DEFAULT ACTIVITY DATA - HARVESTED RICE

Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
ASIA					
Brunei	1	82	79	21	0
Hong Kong	0	123	100	0	0
Syria	0	123	100	0	0
Turkey	52	123	100	0	0
India	42321	107	53	15	32
Pakistan	103	103	100	0	0
Bangladesh	10303	132	14	14	72
Myanmar	4774	139	42	15	43
Nepal	1440	90	29	4	67
Afghanistan	173	103	100	0	0
Bhutan	25	169	21	15	64
China	33265	115	93	2	5
Indonesia	10403	110	78	15	7
Iran	570	103	100	0	0
Iraq	78	123	100	0	0
Japan	2073	123	96	4	0
Malaysia	2073	123	96	4	0
Philippines	3413	98	54	12	34
Sri Lanka	793	122	65	7	28
Taiwan	700	119	97	3	0
Thailand	9878	123	22	12	66
Kampuchea	1800	134	34	27	39
Laos	625	123	11	49	40
Vietnam	6069	119	65	7	28
N Korea	673	103	67	13	20
S Korea	1237	103	91	1	8

Notes: Areas were taken from FAO Yearbook (UN, 1992), China Agricultural Yearbook (1990) and World Rice Statistics (IRRI, 1990)

Season length is an average weighted by area of the adjusted growing season The adjusted growing season uses the crop calendars of Matthews et al., (1991) reduced by 10-45 days. See Shearer and Khalil (1993) for details

"Continuously Flooded" rice is actually the percentage irrigated; "Dry" is the percentage of dryland or upland rice: "Intermittently Flooded" is actually the percentage of shallow rainfed rice. Sources. DeDatta (1975), Huke, (1982), Grist (1986), IRRI (1990).

TABLE 4-11 (CONTINUED)
DEFAULT ACTIVITY DATA - HARVESTED RICE

Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
EUROPE					
Albania	2	123	100	0	0
Bulgaria	11	103	100	0	0
France	20	139	100	0	0
Greece	15	103	100	0	0
Hungary	11	123	100	0	0
Italy	208	102	100	0	0
Portugal	33	123	100	0	0
Romania	37	123	100	0	0
Spain	81	103	100	0	0
Former USSR	624	103	100	0	0
Former Yugoslavia	8	123	100	0	0
PACIFIC					
Australia	97	128	100	0	0
Fiji	13	81	50	0	0
Solomon Islands	0	102	38	0	0
Papua/New Guinea	0	102	38	0	0
AFRICA					
Algeria	1	138	100	0	0
Angola	18	121	100	0	0
Benin	7	123	10	90	0
Burkina Faso	19	123	89	11	0
Burundi	12	167	25	75	0
Cameroon	15	103	25	75	0
C African Rep	10	123	25	75	0
Chad	39	123	25	75	0
Comoros	13	100	100	0	0
Congo	4	121	25	75	0
Egypt	427	123	100	0	0
Gabon	0	121	25	75	0
Gambia	14	123	90	10	0
Ghana	85	139	24	76	0
Guinea Bissau	57	123	25	75	0
Guinea	608	123	8	47	45

Notes: Areas were taken from FAO Yearbook (UN, 1992), China Agricultural Yearbook (1990) and World Rice Statistics (IRRI, 1990)

Season length is an average weighted by area of the adjusted growing season. The adjusted growing season uses the crop calendars of Matthews et al., (1991) reduced by 10-45 days. See Shearer and Khalil (1993) for details.

"Continuously Flooded" rice is actually the percentage irrigated. "Dry" is the percentage of dryland or upland rice "Intermittently Flooded" is actually the percentage of shallow rainfed rice Sources: DeDatta (1975), Huke, (1982), Grist (1986), IRRI (1990)

TABLE 4-11 (CONTINUED)
DEFAULT ACTIVITY DATA - HARVESTED RICE

Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
Ivory Coast	583	123	6	87	7
Kenya	15	139	25	75	0
Liberia	168	123	0	94	6
Madagascar	1135	167	35	19	46
Malawi	29	137	25	75	0
Mali	222	123	25	75	0
Mauritania	14	123	100	0	0
Morocco	6	138	100	0	0
Mozambique	109	121	25	75	0
Niger	29	102	35	65	0
Nigeria	1567	103	28	55	17
Rwanda	3	167	25	75	0
Senegal	73	103	25	75	0
Sierra Leone	339	139	1	67	32
Somalia	5	103	50	50	0
South Africa	1	167	100	0	0
Sudan	1	103	50	50	0
Swaziland	0	167	25	75	0
Tanzania	375	137	10	26	64
Togo	21	139	4	96	0
Uganda	37	137	25	75	0
Zaire	393	101	5	90	5
Zambia	11	121	25	75	0
Zimbabwe	0	121	25	75	0

Notes: Areas were taken from FAO Yearbook (UN, 1992), China Agricultural Yearbook (1990) and World Rice Statistics (IRRI, 1990)

Season length is an average weighted by area of the adjusted growing season. The adjusted growing season uses the crop calendars of Matthews et al., (1991) reduced by 10-45 days. See Shearer and Khalil (1993) for details.

"Continuously Flooded" rice is actually the percentage irrigated; "Dry" is the percentage of dryland or upland rice; "Intermittently Flooded" is actually the percentage of shallow rainfed rice. Sources: DeDatta (1975), Huke, (1982), Grist (1986), IRRI (1990)

TABLE 4-12
SEASONAL AVERAGE EMISSION FACTORS CORRECTED FOR AVERAGE TEMPERATURE

Growing Season Average Temperature	**Emission Factor kg/ha-day**	
	Continuously Flooded	Intermittently Flooded
15	2.91	1.75
16	3.09	1.85
17	3.28	1.97
18	3.48	2.09
19	3.68	2.21
20	3.91	2.34
21	4.14	2.94
22	4.39	2.64
23	4.66	2.80
24	4.94	2.97
25	5.24	3.15
26	5.56	3.34
27	5.90	3.54
28	6.25	3.75
29	6.63	3.98
30	7.03	4.22
31	7.46	4.48
32	7.91	4.75
33	8.39	5.03
34	8.90	5.34
35	9.44	5.66

Source: Khalil (1993), personal communication

Greenhouse Gas Emissions from Agricultural Burning

4.4.1 Introduction

Where there is open burning associated with agricultural practices, a number of greenhouse gases (GHG) are emitted from combustion. All burning of biomass produces substantial CO_2 emissions. However, in agricultural burning, the CO_2 released is not considered to be **net** emission. The biomass burned is generally replaced by regrowth over the subsequent year. An equivalent amount of carbon is removed from the atmosphere during this regrowth, to offset the total carbon released from combustion. Therefore the long term net emissions of CO_2 are considered to be zero. Agricultural burning releases other gases in addition to CO_2 which are by-products of incomplete combustion: methane, carbon monoxide, nitrous oxide, and oxides of nitrogen, among others. These non-CO_2 trace gas emissions from biomass burning are net transfers from the biosphere to the atmosphere. It is important to estimate these emissions in national inventories.[18]

There are two major types of agricultural burning addressed in this section – savanna burning and field burning of crop residues. The approach is essentially the same as that used for non-CO_2 trace gases for all burning of unprocessed biomass, including traditional biomass fuels and open burning of cleared forests. For all these activities, there is a common approach in the proposed methodology, in that crude estimates of non-CO_2 trace gas emissions can be based on ratios to the total carbon released. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. Non-methane volatile organic compounds (NMVOCs) can be treated in a similar way. However, no default values for NMVOC are provided in this version of the *Guidelines*. To handle nitrogen trace gases, nitrogen to carbon ratios are used to derive total nitrogen released and then emissions of N_2O and NO_x are estimated based on ratios of these gases to total nitrogen released. Tables 4-14 and 4-15 provide suggested default values for non-CO_2 trace gas emission ratios. These are presented with ranges, which emphasise their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[19]

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[18] For biomass combustion, CO_2 emissions are frequently not considered **net** emissions, and this is the case for agricultural burning. One could argue, in such cases, that this burning could be considered a short term sink of CO_2. That is, a portion of carbon in biomass is being released as **net** emissions of CH_4 and CO, while regrowth is removing the full amount of the original carbon from the atmosphere in the next cycle. Each year plants take up a certain amount of carbon from the atmosphere. When they are burned some of that carbon is converted to CO, and CH_4, so that an amount less than the total CO_2 which was taken up by the plants is re-emitted as CO_2. See Howden et al. (in press), for a more detailed discussion of this proposal. Treating emissions of CO and CH_4 to the atmosphere, as a sink for atmospheric CO_2, however, is inconsistent with the proposed IPCC emissions methodology. In particular, the other carbon compounds emitted are converted back into CO_2 in the atmosphere over periods of days up to a decade or so. Thus, over the time horizons of interest for CO_2, (i.e. more than 100 years) there is no sink of CO_2.

The calculation of immediate trace gas emissions, based on the default emission ratios provided in Tables 4-14 and 4-15, produces relatively crude estimates with substantial uncertainties.[20] Use of specific emission ratios which vary by type of burning, region, etc. may allow for more precise calculations. The calculations described here ignore the contemporary fluxes associated with past burning activities. These delayed releases are known to exist, but are poorly understood at present. This and other possible refinements are discussed at the end of this section.

4.4.2 Prescribed Burning of Savannas

Background

The term savanna refers to tropical and subtropical vegetation formations with a predominantly continuous grass cover, occasionally interrupted by trees and shrubs (Bouliere and Hadley 1970). These formations exist in Africa, Latin America, Asia, and Australia. The growth of vegetation in savannas is controlled by alternating wet and dry seasons: most of the growth occurs during the wet season; man-made and/or natural fires are frequent and generally occur during the dry season. The global area of savannas is uncertain, in part due to lack of data and in part due to differing ecosystem classifications. Estimates of the areal extent of savannas range from 1300-1900 million hectares world-wide, about 60 per cent of which are humid savannas (annual rainfall of 700 mm or more) and 40 per cent are arid savannas (annual rainfall of less than 700 mm) (Bolin et al., 1979; Whittaker and Likens, 1975; Lanly, 1982; Lacey et al., 1982; and Hao et al., 1990). Large-scale burning takes place primarily in the humid savannas because the arid savannas lack sufficient grass cover to sustain fire. Humid savannas are burned every one to four years on average with the highest frequency in the humid savannas of Africa (as cited in Hao et al., 1990).

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[19] Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible or to provide some expression of the level of confidence associated with various point estimates provided in the inventory. Procedures for reporting this uncertainty or confidence information are discussed in *Volume 1: Reporting Instructions*.

[20] Emission ratios used in this section and presented in the tables are derived from Crutzen and Andreae (1990), Delmas (1993), Delmas and Ahuja (1993) and Lacaux, et al. (1993). They are based on measurements in a wide variety of fires, including forest and savanna fires in the tropics and laboratory fires using grasses and agricultural wastes as fuel. In many cases these ratios are general averages for all biomass burning. Research will need to be conducted in the future to determine if more specific emission ratios, e.g., specific to the type of biomass and burning conditions, can be obtained. Also, emission ratios vary significantly between the flaming and smouldering phases of a fire. CO_2, N_2O, and NO_x are mainly emitted in the flaming stage, while CH_4 and CO are mainly emitted during the smouldering stage (Lobert et al., 1990). The relative importance of these two stages will vary between fires in different ecosystems and under different climatic conditions, and so the emission ratios will vary. As inventory methodologies are refined, emission ratios should be chosen to represent as closely as possible the ecosystem type being burned, as well as the characteristics of the fire.

Savannas are intentionally burned during the dry season primarily for agricultural purposes such as ridding the grassland of weeds and pests, promoting nutrient cycling, and encouraging the growth of new grasses for animal grazing. Savanna burning may be distinguished from other biomass burning activities like open forest clearing because there is little net change in the ecosystem biomass in the savanna after the vegetation regrows during the wet season. Consequently, while savanna burning results in instantaneous gross emissions of CO_2, it is reasonable to assume that the net carbon dioxide released to the atmosphere is essentially zero because the vegetation typically regrows between burning cycles.[21] Savanna burning does release several other important trace gases: methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), oxides of nitrogen (NO_x, i.e., NO and NO_2) and non-methane volatile organic compounds (NMVOCs).

Estimates of global emissions of these gases due to savanna burning have been based on estimates of the annual instantaneous gross release of carbon from this activity and on ratios of the other trace gases released from burning to the total carbon released by burning. Estimates of the annual instantaneous gross release of carbon from savanna burning are highly uncertain because of lack of data on:

- the aboveground biomass density of different savannas;
- the savanna area burned annually;
- the fraction of aboveground biomass which actually burns; and
- the fraction which oxidizes.

The methodology that is proposed in the next section, although conceptually quite simple, takes these factors into account. The approach allows for estimation of non-CO_2 trace gases released by savanna burning, based on default data sets and on assumptions from average literature values for various regions and types of savannas. It also allows for more accurate national estimates if data and assumptions can be developed to reflect national average conditions accurately. Nonetheless, a wide variety of technical details and open scientific issues remain important research topics.

Calculations

There are two basic components to the calculation. First, it is necessary to estimate the total amount of carbon released to the atmosphere from savanna burning. These are not considered to be net emissions, but are needed to derive non-CO_2 trace gas emissions, which are net emissions. What is required is the annual area burned for the various types of savannas, where type is based primarily upon above and belowground biomass, and perhaps climatological conditions and nutrient status. It is generally recommended for all emissions from agriculture that three-year averages of activity data (e.g., hectares burned) be used instead of a single year's data where possible. This is especially important for savanna burning which is highly variable from year to year. This variability should also be taken into account by national experts in planning data collection programmes to provide more accurate inputs to national inventory calculations. If data are not directly available, estimates can be derived based on total savanna area[22] and average percentages of savanna burned annually, as shown in Table 4-13. Based on the area and type of savanna burned, the amount of carbon released can be calculated (a reflection of biomass densities, fractions burned, carbon contents and fractions oxidised). The second component of the calculation is the same as for other biomass burning categories – emission ratios are applied to estimate the amount of trace gas released based on the amount of carbon released (Table 4-14 provides default emission ratios).

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[21] If grazing pressure coupled with burning too often reduces biomass (i.e., degrades the quality of savannas), then this needs to be considered as a carbon dioxide source. This is not assumed in the basic calculations but could be included as a refinement if considered important.

[22] Most countries with significant savanna area should have national statistics on the total area, but FAO publications (e.g. FAO, 1993) also provide country-specific estimates.

TABLE 4-13
REGIONAL SAVANNA STATISTICS

Region[a]	Fraction of Total Savanna that is Burned Annually	Aboveground Biomass Density (t dm/ha)	Fraction of Biomass Actually Burned	Fraction of Aboveground Biomass that is Living
Tropical America	0.50	6.6 ±1.8		
Tropical Asia	0.50	4.9		
Tropical Africa	0.75	6.6 ±1.6		
Sahel zone	0.05-0.15[b]	0.5-2.5[b]	0.95	0.20
North Sudan zone	0.25-0.50[b]	2-4[b]	0.85	0.45
South Sudan zone	0.25-0.50[b]	3-6[b]	0.85	0.45
Guinea zone	0.60-0.80[b]	4-8[b]	0.9-1.0	0.55
Australia	0.05-0.70	2.1-6		

Sources: Hao et al., 1990, except where noted. These figures are growing season average biomass values, considered most appropriate for general default values

[a] Note that these are ecological zones that do not correspond directly to areas with political boundaries of the same name. For example, the North and South Sudan zones include countries other than Sudan and run East-West across the African continent.

[b] Menaut et al (1991) These figures are maximum biomass values. For these arid sub-regions, maximums are considered the most appropriate default values.

Note: Biomass density is in tonnes of dry matter (dm) per hectare (ha).

The approach recognises that countries generally possess more than one savanna type, each with different characteristics, such as vegetative cover, that would affect trace gas emissions from burning. Also, the savanna area within a country may not be burned all at once, but rather in stages over the course of the dry season. Since the amount and nature (e.g., moisture content) of the vegetation changes during the year, factors such as biomass exposed to burning and fraction burned will vary among the savanna areas burned at different times. The data requested by this methodology focus upon country-specific types of savannas and the country-specific rate of burning for each type.[23]

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[23] If the area of savanna is not readily available, then the area of "open, broadleaved forests," including open, broadleaved, fallow areas, as defined by the UN Food and Agriculture Organization in FAO (1993) can be used as an estimate. This land area, corresponds to "mixed broadleaved forest-grassland tree formations with a continuous dense grass layer in which the [woody vegetation covers] more than 10% [of the area]" (Lanly, 1982). FAO (1993) provides 1990 estimates of this area, by country, for tropical America, Asia, and Africa. Hao et al. (1990) provide an estimate of the humid savanna area in Australia, based on work by Lacey et al. (1982).

It is also recognised that national and regional estimates of the percentage of savanna area burned annually are highly uncertain. An example selection of regional estimates is included in Table 4-13. Though regional variability is great, the methodology, by focusing upon a simple classification of savanna type and the burning by type, can be implemented using data that are available to most countries. The methodology is intended to be flexible to allow users to define the savanna types and/or geographic subregions for calculations. It is strongly recommended that national experts consider dividing total savannas into woody savannas and grasslands, if possible. Many countries contain systems which have significant aboveground woody biomass and others which have very little aboveground biomass other than grasses. These subcategories have significantly different biomass densities and fractions oxidised and should be accounted for separately rather than by averaging, if data are available. National experts are encouraged to carry out the calculations at the finest levels of detail for which credible data can be obtained. Finally, by varying assumptions about the rate and/or type of savannas burned, national experts can easily compare the sensitivity of the calculated emissions to the uncertainties in the data.

It should be noted that not all savanna burning occurs from anthropogenic causes. Some natural savanna fires obviously occur, and would occur in the absence of human intervention. As is the case with many human interactions with the biosphere, it is very difficult to establish the net effects of human intervention relative to the natural background, or the conditions which would have occurred naturally in the absence of intervention. In this situation, the recommended conservative default is that all fires are considered anthropogenic, unless they can be documented to be from natural causes. This clearly may overstate the emissions somewhat. National experts may choose to modify this assumption using expert judgement or other sources to allocate the anthropogenic and natural components, provided the rationale is clearly documented.

Step 1: Total Carbon Released From Savanna Burning

In order to calculate the carbon released to the atmosphere from savanna burning, these data are required for each category:

- Area of savanna;
- Fraction of savanna area burned annually;
- Average aboveground biomass density (tonnes dry matter/hectare) of savannas;
- Fraction of aboveground biomass which actually burns;
- Fraction of aboveground biomass that is living;
- Fraction of living and of dead aboveground biomass oxidised; and
- Fraction of carbon in living and dead biomass.

Not all of these data must be provided by the user. Initially one could pool the living and dead biomass if data are not available. More importantly, Table 4-13 provides much of the basic default data that only need to be refined for country-specific relevance. Given the data, the steps to calculate emissions are not overly difficult. One simply calculates from the area burned the total carbon released based upon the factors listed above. In addition to the data in Table 4-13, other recommended default values are included in the step-by-step discussion below.[24]

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[24] It is hoped that individual countries have this information since it is needed to execute the proposed methodology. Regional estimates of these statistics are provided by Menaut (1990) and Hao et al. (1990) and reproduced in a table. More country-specific

The following equations summarise the calculations to estimate the total carbon released due to the burning of savannas for each category:

EQUATION 1

Area of Savanna Burned Annually (ha)

=

Total Area of Savanna (ha) x Fraction Burned Annually

EQUATION 2

Biomass Burned (t dm)

=

Area of Savanna Burned Annually (ha)
x Aboveground Biomass Density (t dm/ha) x Fraction Actually Burned

EQUATION 3

Carbon Released from Live Biomass (t C)

=

Biomass Burned (t dm) x Fraction that is Live x Fraction Oxidised
x Carbon Content of Live Biomass (t C/t dm)

EQUATION 4

Carbon Released from Dead Biomass (t C)

=

Biomass Burned (t dm) x Fraction that is Dead x Fraction Oxidised
x Carbon Content of Dead Biomass (t C/t dm)

EQUATION 5

Total Carbon Released (t C)

=

C Released from Live Material (t C) + C Released from Dead Material (t C)

In the first equation, the savanna area in the country is multiplied by the percentage of the savanna area that is burned annually. if statistics on area burned annually are not directly

research is clearly needed on this issue before accurate inventories can be developed. This research should include data on savanna area burned annually, savanna biomass densities, live fractions of biomass, burning efficiencies, and carbon contents of savanna biomass. In the meantime, default values can be used.

available. If national experts have data on the area burned annually they should use this and begin with equation 2. In the second, area burned is multiplied by aboveground dry biomass per hectare (ha) on the savanna at the time of burning and the fraction of biomass which actually burns. Regional estimates of rates of savanna burning and biomass densities are presented in Table 4-13. The fraction actually burned accounts for the fact that when savannas are burned, not all of the biomass on each hectare is actually exposed to flame. If detailed information is not available, a general default value in the range of 0.80-0.85 is recommended (Delmas and Ahuja, 1993).

The aboveground biomass density before burning is a function of the type of savanna being burned and the time of year in which burning occurs.[25] The values for West African savannas provided in Table 4-13 correspond to mid-season fires, except for those of the Sahel where burning occurs early. If statistics on maximum biomass density and fraction of maximum biomass density present at the time of burning are not available, countries can use an average biomass density instead. According to this analysis, average savanna biomass densities are lowest in tropical Asia, at about 5 tonnes per hectare (t/ha) (Singh and Misra, 1978), average around 6.6 t/ha in tropical Africa and tropical America (San José and Medina, 1976; González-Jiménez, 1979; Coutinho, 1982; Hopkins, 1965; Haggar, 1970; Menaut and César, 1982; and Huntley and Morris, 1982). The densities range between 2 and 6 t/ha in Australia (Lacey et al., 1982). These estimates have an uncertainty of ± 30 per cent based on field measurements (Hao et al., 1990). As mentioned, these regional average densities are presented in Table 4-13 and can be used as default values if average biomass density for a specific country or savanna type is not known.

In the third and fourth equations, the living and the dead portions of aboveground biomass burned are multiplied by their respective fractions oxidised and carbon contents. Estimates of the fraction of aboveground biomass that is living for West African savannas range from 20 to 55 per cent (Table 4-13). Data suggest that for the live portion, the fraction which burns ranges between 65 and 95 per cent and for the dead portion essentially 100 per cent burns (Menaut et al., 1991). If fractions oxidised are not available, 80 per cent and 100 per cent for the living and dead portions, respectively, can be used. If country or ecosystem values are not available, then the values 0.45 t C/t dry biomass and 0.40 t C/t dry biomass can be used as default values for the carbon contents of the living and dead portions, respectively (Menaut et al., 1991).

The total carbon released from savanna burning (Equation 5) is estimated by summing the carbon released from the living and the dead biomass fractions, calculated in Equations 3 and 4.

Step 2: Emissions

Once the carbon released from savanna burning has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated using emission ratios. (Default values are presented in Table 4-14.)[26] The amount of carbon released due to burning is multiplied by the emission ratios of CH_4 and CO relative to total carbon released to yield emissions of CH_4 and CO (each expressed in units of C). The emissions of CH_4 and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights. NMVOC could also be calculated in the same way. However, default values are not available in this edition of the *Guidelines*.

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[25] Menaut et al. (1991) calculate this number by multiplying the maximum biomass density of the savanna (which generally is reached at the end of the growing season) by a coefficient that declines as the burning occurs later in the dry season.

[26] This approach is adapted from Crutzen and Andreae, 1990, with some values updated, based on more recent studies by Delmas (1993), Delmas and Ahuja (1993) and Lacaux et al. (1993).

To calculate emissions of N_2O and NO_x, first the carbon released is multiplied by the estimated ratio of nitrogen to carbon (N/C ratio) in savanna biomass by weight (0.006 is a general default value for savanna biomass burning (Crutzen and Andreae, 1990)). This yields the total amount of nitrogen (N) released from the biomass burned. The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the N released to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28 and 46/14, respectively.[27]

The non-CO_2 trace gas emissions calculations from burning are summarised as follows:

CH_4 Emissions = (carbon released) x (emission ratio) x 16/12

CO Emissions = (carbon released) x (emission ratio) x 28/12

N_2O Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 44/28

NO_x Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 46/14

TABLE 4-14
EMISSION RATIOS FOR SAVANNA BURNING CALCULATIONS

Compound	Ratios	
CH_4 [1]	0.004	(0.002 - 0.006)
CO [2]	0.06	(0.04 - 0.08)
N_2O [3]	0.007	(0.005 - 0.009)
NO_x [3]	0.121	(0.094 - 0.148)

Sources:

[1] Delmas, 1993

[2] Lacaux, et al., 1993

[3] Crutzen and Andreae, 1990

Note Ratios for carbon compounds, i.e., CH_4 and CO, are mass of carbon compound released (in units of C) relative to mass of total carbon released from burning (in units of C), those for the nitrogen compounds are expressed as the ratios of mass of nitrogen compounds released relative to the total mass of nitrogen released from the fuel

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[27] The molecular weight ratios given above the emitted gases are with respect to the weight of nitrogen in the molecule. Thus for N_2O the ratio is 44/28 and for NO_x it is 46/14. NO_2 has been used as the reference molecule for NO_x.

4.4.3 Field Burning of Agricultural Residues

Background

Large quantities of agricultural wastes are produced, from farming systems world-wide, in the form of crop residue.[28] Burning of crop residues, like the burning of savannas, is not thought to be a net source of carbon dioxide (CO_2) because the carbon released to the atmosphere during burning is reabsorbed during the next growing season. However, crop residue burning is a significant net source of CH_4, CO, NO_x, and N_2O. This section accounts for emissions of these non-CO_2 gases from field burning of agricultural crop residues. Burning of agricultural crop residues as an energy source is covered in the *Energy* chapter, in the section entitled *Burning Traditional Biomass Fuels*.

The amount of agricultural wastes produced varies by country, crop, and management system. For example, cereal crops produce between 0.6 and 2.5 tonnes of straw per tonne of grain (Barnard, 1990; Ponnamperuma, 1984), and wetland rice cultivated under a moderate level of management in the Philippines was found to produce between 0.6 and 0.9 tonnes of straw per tonne of grain (Ponnamperuma, 1984). Approximately 3.1 billion tonnes of crop residue are produced each year, with about 60 per cent originating in the developing world, and 40 per cent in the developed world (Strehler and Stützle, 1987).

Burning of agricultural wastes in the fields is a common practice in the developing world. It is used primarily to clear remaining straw and stubble after harvest and to prepare the field for the next cropping cycle. In Southeast Asia, burning is the major disposal method for rice straw (Ponnamperuma, 1984), which accounts for about 31 per cent of the agricultural waste in the developing world. Sugar cane residues, which make up about 11 per cent of the world's agricultural waste, are primarily disposed of by burning (Crutzen and Andreae, 1990). It has been estimated that as much as 40 per cent of the residues produced in developing countries may be burned in fields, while the percentage is lower in developed countries (Barnard and Kristoferson, 1985). Another study suggests that approximately 425 Tg dry matter agricultural wastes (~200 Tg C) are burned in the fields in developing countries and that about one-tenth as much is burned in developed countries (Crutzen and Andreae, 1990).

Calculations

The methodology for estimating greenhouse gas emissions from burning of agricultural wastes is based, as in savanna burning, on 1) total carbon released, which is a function of the amount and efficiency of biomass burned and the carbon content of the biomass, and 2) the application of emission ratios of CH_4 and CO to total carbon released, and of N_2O and NO_x to total nitrogen released from biomass fires which are available from the scientific literature on biomass burning. It is generally recommended for all emissions from agriculture and land use change, that three-year averages of activity data (e.g., crop residues burned) be used if available.

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[28] Barnard (1990) outlines several broad categories of crop residue: woody crop residues (coconut shells, jute sticks, etc.), cereal residues (rice and wheat straw, maize stalks, etc.), green crop residues (groundnut straw, soybean tops, etc.), and crop processing residues (bagasse, rice husks, etc.).

Step 1: Total Carbon Released from Burning Agricultural Residues

Data required, for each crop type, to calculate the amount of carbon burned in agricultural wastes are listed below:

- Amount of crops produced with residues that are commonly burned;
- Ratio of residue to crop product;
- Fraction of residue burned;
- Dry matter content of residue;
- Fraction oxidised in burning; and
- Carbon content of the residue.

There are standard default or literature values available for many of these data. Table 4-16 provides a summary of available default data. The most important data for users to provide are the actual amount of crops produced (by type) with residues that are commonly burned. Annual crop production statistics by country for most of the crops from which residues are burned are given in the *FAO Production Yearbooks*. Users may also find the *United Nations World Trade Yearbooks* useful. Crop-specific data for each country on ratios of residue to crop, fraction of residue burned, dry matter content of residue, and carbon content of residue can be incorporated at any time to replace the default values. A potentially valuable data source is the recent BUN/UNCED study by Professor D. Hall (and others) of Kings College, London. In this context, one should also note the book *Renewable Energy: Sources for Fuels and Electricity* edited by Johansson et al. (1992).

From production data one can estimate the actual material (in carbon units) that is burned. One simple procedure is shown below:

Total carbon released (tonnes of carbon) =

$$\sum_{\text{all crop types}} \text{annual production (tonnes of biomass per year)},$$

x the ratio of residue to crop product (fraction),

x the average dry matter fraction of residue (tonnes of dry matter / tonnes of biomass),

x the fraction actually burned in the field,

x the fraction oxidised,

x the carbon fraction (tonnes of carbon / tonnes of dry matter)

It is highly desirable to use country-specific data for these values wherever possible. Example estimates of residue/crop product ratios, average dry matter fraction and carbon fraction for certain crops are presented in Table 4-16.[29] If no other data are available, the following assumptions regarding the fraction of crop residue burned in the field can be used as very crude default factors: for developing countries 0.25, and for developed countries a much smaller share possibly, 0.10 or less.[30] A default value of 0.90 for fraction oxidised can be used to account for the approximate 10 per cent of the carbon that remains on the ground as a result of charcoal formation and other aspects of incomplete combustion (Seiler and Crutzen, 1980; and Crutzen and Andreae, 1990).

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[29] Dry matter (dm), or dry biomass, refers to biomass in a dehydrated state. According to Elgin (1991), the moisture content of crop residue varies depending on the type of crop residue, climatic conditions (i.e., in a humid environment the residue will retain more moisture than in an arid environment), and the length of time between harvesting and burning of the residue. From a simple perspective, one can use the dry matter content values in Table 4-16 to convert from total crop residue to dry matter. For example, 200 tonnes of crop residue with a moisture content of 10%, would have a dry matter content of 90%, equal to 180 tonnes of dry matter. To convert from dry matter to carbon content, an average value of 0.45 t C/t dm can be used in the cases where crop specific

Step 2: Gas Emissions

Once the carbon released from field burning of agricultural resides has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated based on emission ratios (default values are provided in Table 4-15).[31] The amount of carbon released due to burning is multiplied by the emission ratios of CH_4 and CO relative to total carbon to yield emissions of CH_4 and CO (each expressed in units of C). The emissions of CH_4 and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights. NMVOC could also be calculated in the same way. However, default values are not available in this edition of the *Guidelines*.

To calculate emissions of N_2O and NO_x, first the total carbon released is multiplied by the estimated N-C ratio of the fuel by weight to yield the total amount of nitrogen (N) released. Some crop-specific values are given in Table 4-16 and 0.015 is a general default value for crop residues.[32] The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the N content of the fuel to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28 and 46/14, respectively.[33]

The calculation for trace gas emissions from burning is summarised as follows:

CH_4 Emissions = Carbon Released x (emission ratio) x 16/12

CO Emissions = Carbon Released x (emission ratio) x 28/12

N_2O Emissions = Carbon Released x (N/C ratio) x (emission ratio) x 44/28

NO_x Emissions = Carbon Released x (N/C ratio) x (emission ratio) x 46/14

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data are not available. The terms dry matter and dry biomass are used interchangeably in this text.

[30] Crutzen and Andreae, 1990. The estimates are very speculative and should be used with caution. The actual percentage burned varies substantially by country and crop type. This is an area where locally developed, country-specific data are highly desirable. As this issue is studied further, it may be possible to incorporate more accurate, country-and crop-specific percentages into future editions of the *Guidelines*.

[31] This approach is adapted from Crutzen and Andreae, 1990, with some values updated based on more recent studies by Delmas (1993), Delmas and Ahuja (1993) and Lacaux et al. (1993).

[32] Crop specific values are generally in the range of 0.01-0.02, from Crutzen and Andreae, 1990, so that 0.015 can be used as a generally representative value if no other information is available.

[33] The molecular weight ratios given above for the emitted gases are with respect to the weight of nitrogen in the molecule. Thus for N_2O the ratio is 44/28 and for NO_x it is 46/14. NO_2 has been used as the reference molecule for NO_x.

TABLE 4-15
EMISSION RATIOS FOR AGRICULTURAL RESIDUE BURNING CALCULATIONS

Compound	Ratios
CH_4 [1]	0.005 Range 0.003 - 0.007
CO [2]	0.06 Range 0.04 - 0.08
N_2O [3]	0.007 Range 0.005 - 0.009
NO_x [3]	0.121 Range 0.094 - 0.148

Sources:

[1] Delmas, 1993

[2] Lacaux, et al., 1993

[3] Crutzen and Andreae, 1990

Note: Ratios for carbon compounds, i.e., CH_4 and CO, are mass of carbon compound released (in units of C) relative to mass of total carbon released from burning (in units of C); those for the nitrogen compounds are expressed as the ratios of mass of nitrogen compounds relative to the total mass of nitrogen released from the fuel.

TABLE 4-16
SELECTED CROP RESIDUE STATISTICS

Product	Residue/Crop Product	Dry Matter Fraction	Carbon Fraction (% dm)	Nitrogen-Carbon (N-C) Ratio
Wheat	1.3	0.78-0.88	0.4853	0.012
Barley	1.2	0.78-0.88	0.4567	
Maize	1	0.30-0.50	0.4709	0.02
Oats	1.3			
Rye	1.6			
Rice	1.4	0.78-0.88	0.4144	0.014
Millet	1.4			0.016
Sorghum	1.4			0.02
Pea	1.5			
Bean	2.1			
Soya	2.1			0.05
Potatoes	0.4	0.30-0.60	0.4226	
Feedbeet	0.3	0.10-0.20 [1]	0.4072[1]	
Sugarbeet	0.2	0.10-0.20 [1]	0.4072[1]	
Jerusalem artichoke	0.8			
Peanut	1			

Sources: Strehler and Stutzle, 1987

Sugarbeet data from Ryan and Openshaw, 1991

Nitrogen content from Barnard and Kristoferson, 1985

[1] These figures are for beet leaves

Possible refinements of the basic calculations

The basic calculations presented above address the immediate release of non-CO_2 trace gases when savannas or crops are burned. This is believed to be the most important effect of biomass burning on GHG emissions and the best characterised at present. However, there are other issues not treated in these calculations. The effect of past burning on current emissions is one such issue. The longer-term release or uptake of these gases following burning is an important research issue and may be included in future refinements of the calculations. In particular, grassland fires (savanna burning) may perturb the soils sufficiently to release additional N_2O and NO_x. Little is known about the magnitude of this flux so these emissions are not included in the first application of the methodology. It is less likely that such delayed releases are significant after field burning of agricultural residues, but this may also require further study.

Long term changes in soil carbon are certainly possible as a result of agricultural practices. In the land use change and forestry chapter, there is a general default assumption that soil carbon is gradually lost from agricultural lands over many years after forests are cleared. In fact, depending on the specific agricultural and soil management practices (including burning) which are used, there may be a variety of effects on soil carbon. For example, repeated burning of savannas and crop residues in fields may cause an increase in the amount of carbon stored in the soil over time. This is an area which requires further research and may lead to more detailed emissions estimation methods in the future.

In addition, agricultural practices such as overgrazing which degrade the productivity of grasslands or other agricultural lands, reduce the amount of aboveground biomass which regrows. These could be considered sources of gradual emissions of carbon dioxide. This situation is not included in the basic calculations, but could be included in more refined calculations. National experts should determine whether or not this is important for their country, and whether or not they are able to provide input data.

A similar long-term effect can be observed from savanna burning. If the savannas are burned too frequently, complete regrowth may not occur. In this situation, grasslands can degrade over time, resulting in long-term losses of both aboveground and soil carbon. If this condition is significant, national experts are encouraged to estimate the annual effect and explain the assumptions and data used.

Another possible refinement is to account for carbon that might be sequestered through the use of agricultural residues to make durable products (e.g., bricks, composite boards). The default assumption is that the carbon sequestered in such activities on an annual basis is small, and can be ignored in the calculations, that is, as long as the stocks of such products are not significantly increasing or decreasing over time, their effect on emissions/removals can be ignored. If national experts believe the effects may be significant, they are encouraged to estimate this carbon sink and document the assumptions and data used.

4.5 Greenhouse Gas Emissions from Agricultural Soils

4.5.1 Introduction

Agricultural soils may emit or remove nitrous oxide (N_2O), carbon dioxide (CO_2) and/or methane (CH_4). For example, peat compost used as a soil amendment in agriculture and gardening may result in CO_2 emissions or removals. A methodology for estimating N_2O from agricultural soils is presented here, but currently available data do not support methodologies for estimating CO_2 or CH_4 emissions from or removals by agricultural soils. The development of methodologies for estimating emissions of carbon dioxide and methane from agricultural soils and the improvement and refinement of the methodology for estimating nitrous oxide emissions have been identified as areas for future work.

This chapter covers emissions of nitrous oxide (N_2O) from agricultural soils. Estimates of N_2O emissions from the biosphere into the atmosphere are highly uncertain, but it is believed that about 70 per cent originate from soils (Bouwman, 1990; Houghton et al., 1992). It seems reasonable then, to assume that changes in nitrogen cycling in soil systems have influenced the increases in atmospheric N_2O during the past century and will help dictate future changes in atmospheric N_2O. A direct effect, that can be quantified, is the increase in nitrogen input into the soil systems. This increase in nitrogen input is partly derived from atmospheric deposition, which ranges from about 0.5 g N m^{-2} yr^{-1} in the central US to 6 g N m^{-2} yr^{-1} in western Europe (Andreae and Schimel, 1989), nitrogen fertilisation with mineral nitrogen sources or animal excreta and biological nitrogen fixation, and soil organic matter mineralisation.[34] Nitrogen fertiliser use and biological N-fixation are projected to continue to increase during the next 100 years (Hammond, 1990).

To determine N_2O emissions from agricultural soils for various parts of the earth, we must predict how much N_2O is produced from each unit of chemically or biologically fixed N that is added to the soil. To make this prediction we first must understand how and where N_2O is produced in the biosphere, what sinks exist for the gas, and how the gas moves from where it is produced into the atmosphere. Research during the past several decades provides an understanding of how N_2O is produced, factors that control its production, source/sink relationships, and gas movement processes. However, even with this large amount of knowledge, we are not yet able to reliably predict the fate of a unit of nitrogen that is applied or deposited on a specific agricultural field. Studies of emissions of N_2O from presumably "similar" agricultural systems show highly variable results in both time and space. It is the complex interaction of the physical and biological processes involved that must be understood before appropriate predictive capability can be developed.

It is surprising that during the last few years, with the renewed interest in climate change and the role played by certain trace gases, little new information concerning emissions of N_2O from agricultural fields has been published. Many recent review papers and inventory assessments have all relied on published gas flux measurements from studies conducted, primarily, during the late 1970's and early 1980's. The number of flux measurements and the variety of soil conditions examined are limited. Therefore, the data from which these reviews and inventories have been drawn are also limited and because of the limitations, inappropriate conclusions may have been drawn.

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[34] Human waste is sometimes used as fertiliser for agricultural soils, and can result in emissions or removals of CH_4, N_2O or CO_2. This issue is discussed in Box 1 "Human Waste Used As Fertiliser" of the Agriculture subchapter "Methane Emissions from Domestic Livestock: Enteric Fermentation and Manure."

As noted in the OECD/OCDE (1991) report, we know that N_2O is produced primarily from the microbial processes of nitrification and denitrification in the soil. In well aerated conditions, where soil moisture content is low enough not to limit aeration, N_2O emissions from nitrification of ammonium-based fertilisers can be substantial (Bremner and Blackmer, 1978; Duxbury and McConnaughey, 1986). Other work suggests that N_2O release is a by-product of nitrification (Yoshida and Alexander, 1970) and may occur by denitrification of nitrite by nitrifying organisms under oxygen stress (Poth and Focht, 1985). Recent evidence indicates that in well aerated, porous soils, little N_2O may evolve during nitrification, but much larger amounts of NO may be emitted (Williams et al., 1993). In wet soils where aeration is restricted, denitrification is generally the source of N_2O (Smith, 1990). Under these conditions both the rate of denitrification and the $N_2O/(N_2 + N_2O)$ ratio must be known to evaluate N_2O emissions through denitrification. According to Smith (1990), soil structure and water content affect the balance between diffusive escape of N_2O and its further reduction to N_2, and are important among the factors determining the proportions of the two gases.

Research has also shown us that a number of individual factors are controllers of nitrification and denitrification. These factors include:

- soil water content, which regulates oxygen supply;
- temperature, as most organisms have a temperature range over which reaction rates are optimal;
- nitrate or ammonium concentration, since substrates may individually regulate reaction rates and in the case of denitrification regulate the N_2O/N_2 ratio;
- available organic carbon, because denitrifiers require a usable organic carbon source and microbial respiration of organic carbon may also regulate oxygen supply; and
- pH, which is a controller of both nitrification and denitrification and the N_2O/N_2 ratio in denitrification.

Increases in the amount of nitrogen added to the soil generally increases N_2O emissions from the soil (Bouwman, 1990). The temporal pattern of N_2O emissions following fertilisation is generally that of a large efflux of N_2O occurring for a short time (about six weeks). After this time, emission rates are reduced to fluctuate around a low base-line level independent of the amount of fertiliser applied (Mosier et al., 1983). Some studies indicate that N_2O emission rates are higher for ammonium-based fertilisers than for nitrate (Eichner, 1990). For example, Bremner et al. (1981) found a much higher proportion of N_2O released from anhydrous ammonia than from urea or ammonium sulphate. Bouwman's (1990) review, however, suggested no particular trend in N_2O emissions related to fertiliser type. Byrnes et al. (1990) suggest that N_2O emissions from the nitrification of fertilisers may be more closely related to soil properties than to the nitrogen source that is supplied. Mineral nitrogen applications along with organic matter amendments generally increase total denitrification and N_2O production.

As discussed in more detail by Mosier (1989), N_2O emissions from the soil can vary by orders of magnitude from a location both spatially and temporally. These heterogeneities in measured gas fluxes and in the microbial activity which produces the gases make predictions highly uncertain.

External factors also perturb "normal" soil nitrogen cycling and thus increase N_2O emissions. Land use conversion has been a primary factor in the past (Houghton and Scole, 1990), and conversion of forests and grasslands to croplands accelerated carbon and nitrogen cycling and increased N_2O emissions from the soil. Globally, land use conversion is important now only in tropical areas. Most of the conversions of forests and grasslands in the northern hemisphere occurred 50 to 200 years ago (Hammond, 1990). Global changes may impart changes in soil temperature and moisture which will directly influence nitrogen cycling.

4.5.2 1991 OECD N_2O Emission Methodology

The first OECD/OCDE (1991) methodology for calculating N_2O emissions from nitrogen fertilisers was based on the amount of each type of commercial fertiliser nitrogen consumed (in mass units of N), an emission coefficient for the fraction of applied nitrogen that is released as N_2O-N for each fertiliser type, and a ratio used to convert the emission from N_2O-N to N_2O. Emissions of N_2O-N are estimated from each fertiliser type, summed over all types, and then converted to units of N_2O:

$$N_2O\text{-N Emissions (tonnes } N_2O\text{-N)} = \sum_f (F_f \times E_f) \qquad (1)$$

where: F = Fertiliser Consumption (tonnes N)

E = Emission Coefficient (Tonnes N_2O-N released/tonne N applied)

f = Fertiliser type

N_2O Emissions (tonnes N_2O) = N_2O-N Emissions (tonnes N_2O-N) x 44/28.

The Working Group suggested dropping the attempt to calculate N_2O emissions based on the type of commercial fertiliser nitrogen applied. Considering the number of agricultural systems that exist world wide and the number of sources of nitrogen available for use, the data set available for these analyses is quite small. As a result, single studies at single locations can dominate, and possibly skew the analysis. Another point is that since most of the data cited were from studies conducted only during the cropping season, or part of the cropping season, little is known about nitrogen emissions following crop harvest and before planting in the spring. Recent research (Sommerfeld et al., 1993) indicates that appreciable N_2O emissions can occur from snow-covered soils and Goodroad and Keeney (1984) noted large fluxes of N_2O during winter thaw periods. The Expert Group concluded that there is no justification for including fertiliser type in the equation, as existing data show wide, overlapping ranges of emission factors for each commercial fertiliser type. Many studies show that interacting field variables such as soil type, soil water content, and substrate availability regulate N_2O emissions rather than nitrogen source.

The second OECD/OCDE (1991) methodology includes the fertiliser source variable, and also includes the crop type to which the fertiliser is applied. This approach is the same as the first except that emissions of N_2O-N are summed over all fertiliser and crop types, instead of just over all fertiliser types.

$$N_2O\text{-}N \text{ Emissions (tonnes } N_2O\text{-}N) = \sum_{fc} (F_{fc} \times E_{fc}) \qquad (2)$$

where: F = Fertiliser Consumption (tonnes N)

E = Emission Coefficient (tonnes N_2O-N released/tonne N applied)

f = Fertiliser type

c = Crop type

N_2O Emissions (tonnes N_2O) = N_2O-N Emissions (tonnes N_2O-N) x 44/28

Including crop type in the calculation seems reasonable since the type of crop tends to regulate soil water content, the timing of mineral nitrogen uptake, and the release of mineralisable carbon into the soil. All of these factors are regulators of N_2O-forming processes. But as noted in OECD (1991) there is not enough information to calculate the necessary coefficients for each crop type. This calculation is therefore no longer recommended.

4.5.3 Issues discussed by the Expert Group

As the data available from which to calculate N_2O emission coefficients from either nitrogen fertiliser source or crop type are not adequate to make such calculations, and it is unlikely that within the next few years sufficient studies will be conducted to make adequate coefficient calculations, the Expert Group suggested the following, simplified calculation for estimating N_2O emissions from agricultural soils:

(3) N_2O-N Emission (tonnes N_2O-N) = F x 0.01

where: F = Total Fertiliser Consumption (tonnes N)

(4) N_2O Emissions (tonnes N_2O) = N_2O-N Emission (tonnes N_2O-N) x 44/28

Because of the limitations of the data available and the scope of the data, a value of 1 per cent/year of fertiliser (both mineral and organic) nitrogen direct emission from agricultural fields does not seem unreasonable. The literature on field N_2O flux are adequate to provide the order of magnitude of the multiplication coefficient, greater than 0.001 and less than 0.1 (CAST, 1992).

There is certainly room for arguing the validity of this suggestion. For example in a flooded rice field, when fertiliser nitrogen is added immediately before flooding, little N_2O is emitted (Freney et al., 1981). We do not know, however, how much N_2O evolves from the field when the water is drained for harvest or during the intercrop dry period. Some evidence indicates that appreciable N_2O is evolved from a rice field during the first few days after the field is flooded (Byrnes et al., 1993). A simple equation relating soil mineral nitrogen content and soil per cent water-filled pore space to N_2O emissions integrated through the entire year may represent N_2O emissions reasonably well. There is, unfortunately, no possibility to link this to national inventory calculations.

The second major point discussed by the Expert Group was that the OECD (1991) method only addressed direct N_2O emissions from cultivated agricultural soils that had been fertilised with commercial fertiliser nitrogen. The consensus of the group was that this narrow concept is not appropriate since nitrogen from (1) atmospheric deposition, (2) commercial fertiliser, (3) animal excreta[35] and plant residues, (4) biological N fixation, and (5) soil organic matter mineralisation should all be considered in the equation. World-wide, the amount of nitrogen input into agricultural systems from animal excreta and biological N fixation is roughly the same as the input from commercial fertiliser nitrogen (about 80 Tg in 1990). Nitrogen input from atmospheric deposition varies globally from about 1 to 50 kg N ha^{-1} yr^{-1} while nitrogen from mineralisation of soil organic matter may vary from 10 to 200 kg N ha^{-1} yr^{-1}; both are site dependent. Currently available data are not adequate to support a methodology for estimating the effect of these factors on N_2O emissions. This has been identified as a priority area for future work.

4.5.4 Recommended methodology

Based upon information that is considered to be available in most countries, the following N_2O emission calculation method is suggested:

a) Low Estimate

$$\boxed{N_2O \text{ Emission} = \Sigma\,(F_{mn} + F_{on} + F_{bnf}) \times C_L}$$

b) High Estimate

$$\boxed{N_2O \text{ Emission} = \Sigma\,(F_{mn} + F_{on} + F_{bnf}) \times C_H}$$

c) Median Estimate

$$\boxed{N_2O \text{ Emission} = \Sigma\,(F_{mn} + F_{on} + F_{bnf}) \times C_M}$$

Where F_{mn} = amount of mineral N applied

F_{on} = amount of organic N applied (animal excreta and crop residue)

F_{bnf} = amount of biological N fixation

C_L = low end of emission coefficient range

C_H = high end of emission coefficient range

C_M = median emission coefficient

Units are in Tg of N for input and Tg N_2O-N x 44/28 for total N_2O emission. It is recommended that national experts use three year averages for activity data if available, so that the data will not be skewed in the event that the base year of the inventory was an exceptional year, and not representative of the country's normal activity level. Box 2 provides example ranges of emission coefficients based on available preliminary analyses. These are somewhat different, but all reflect the key conclusion that all estimates of N_2O emissions are subject to very large ranges of uncertainty. National experts should use one of these available ranges or substitute locally available information (with documentation) if desired. These numbers span the range of most measured N_2O emissions. Because the range of measured N_2O emissions from different agricultural systems is so large, the whole range must be considered to convey the uncertainty in using these estimates.

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[35] Any animal waste which contributes organic N to agricultural soils – e.g., manure, urine, animal waste dropped in the field – can be included in the calculation if national experts are able to provide data.

Box 2

RANGES OF EMISSION COEFFICIENTS FOR N_2O FROM AGRICULTURAL SOILS

	Expert Group Recommendation 1993[1]	Alternative Calculations[2]	Recent Analyses[3]
Low (C_L)	0.0005	0.0014	0.0025
Median (C_M)	0.0036	0.0034	0.0125
High (C_H)	0.039	0.037	0.0225

[1] These values were suggested by the expert group in its report from the Amersfoort Workshop (Bouwman and Mosier, 1993), consistent with its recommendation to drop the distinctions in emission factors for different types of chemical fertiliser. That report explained that these values were derived from Table 5-10 (page 5-51) of the OECD/OCDE (1991) report. The separate emission factors by type of fertiliser were combined by summing the total N_2O emissions and total tonnes N applied across all fertiliser types. Total N_2O emissions were then divided by total N applied to derive high, low and median emission factors for N_2O independent of fertiliser type. In the review of the draft *Guidelines*, however, it was noted that this table was weighted, based on the mix of fertiliser types used in the Netherlands, and thus was not necessarily a good representation of global average conditions.

[2] In response to comments on the draft *Guidelines*, a range of coefficients was calculated based on figures in Table 5-9 (page 5-50) of the OECD/OCDE (1991) report. This table includes specific emission factors which had been proposed for different fertiliser types. These high, low and median values were simply averaged to obtain more general coefficients, independent of fertiliser type.

[3] Recently, Mosier (1994) has provided results of a more detailed analysis of a large amount of measurement data currently available. Although as yet unpublished, these results are presented for comparison.

Note: Although the values from the three different analyses differ somewhat, they all reflect the key findings which the expert group intended to convey in the 1993 Amersfoort workshop report. These are;

- that there is a huge range of uncertainty in any national estimate of N_2O emissions from agricultural soils based on currently available understanding; and,
- that the significant differences reported for specific types of chemical fertiliser are not supported by the data and should not be used.

Most of the information to calculate N_2O emissions are available for many countries, but part may not be readily available for other countries:

a) nitrogen from commercial fertiliser. Total nitrogen consumption as well as mean nitrogen-application level (in kg/ha of arable land) is available for all countries in the FAO Fertiliser Yearbooks (e.g. FAO, 1990a).

b) nitrogen from animal excreta. Animal population data is available from the FAO Production Yearbooks (e.g. FAO, 1990b). The amount of nitrogen in the excreta and the volatilisation of ammonia are well known for most parts of the world. Where such data are not available, estimates can be made based on animal diet. Further data required are: the portion of the year that animals are grazed and confined, and the portion of the excreta collected in the stables and the portion applied to the soil.

The working group on NH_3 of the Global Emission Inventories Activity (GEIA), a core project of the International Global Atmospheric Chemistry Program (IGAC) will develop a methodology to estimate the above parameters. For countries having difficulties to obtain the data, these GEIA-estimates could be used as default values.

c) nitrogen from biological N-fixation. Data on the areas cropped to leguminous crops, such as alfalfa, pulses, soy beans, are readily available from FAO Production Yearbooks (e.g. FAO, 1990b). Commonly, leguminous crops are not fertilised with commercial nitrogen, or are fertilised only with a small amount of starter nitrogen. It is difficult to estimate the amount of N fixed by the crop if we do not know the amount of soil nitrogen before sowing and after harvest, as well as the yield and per cent N in the crop.

4.5.5 For the Future

The OECD Expert Group made the following suggestions for improving the methodology for estimating N_2O emissions from agricultural soils:

1 The assumption that N_2O emissions directly from fertilisers are relatively small should be reviewed. A critical look at the reviews of Eichner (1990), Bouwman (1990) and CAST (1992) indicate that a conservative estimate of direct emission of N_2O from mineral fertiliser over a full year are in the range of 1 per cent of the nitrogen applied, currently about 1 Tg, or about 10 per cent of current global emissions. This estimate does not include either organic nitrogen fertiliser from human and farm animal excreta or nitrogen from biological N fixation. Limited data suggest that N_2O emissions from these nitrogen sources are generally greater than from mineral nitrogen application (Bouwman, 1990). Assuming that nitrogen emissions from all sources are equal, the direct emissions from all three sources could total 3 Tg annually.

2 Although the individual factors that regulate N_2O production are known, we cannot predict how these factors interact under field conditions to produce measured fluxes (OECD/OCDE, 1991). Both nitrification and denitrification and the regulators of N_2O/N_2 ratios from denitrification have their own set of optimum conditions. As a result, one process may be the primary N_2O producer in one set of field conditions, but as soil conditions change, another process may predominate. The complexity of the interactive factors important to the different processes obviously make a simple description of N_2O production difficult (Mosier et al., 1983). Complex models such as that described by Li et al. (1992) may be the only way that N_2O fluxes can be predicted. Simpler, mechanistic models such as that described by Parton et al. (1988) may, however, play a role in simplifying estimation of N_2O emission. To accurately compile an inventory of N_2O emissions from agricultural soils we must be able to predict N_2O emissions based on nitrogen application, soil, crop and management.

It is also likely that N_2O production resulting from fertiliser and biological nitrogen fixation is underestimated because the effect of a nitrogen input is usually only partially traced through the environment. In an example taken from Duxbury et al (1993), 50 of the 100 kg ha^{-1} of N applied as fertiliser on a typical dairy farm are harvested in the crop, and 50 are lost by the combination of leaching (25), surface run-off (5), and volatilisation (20, primarily denitrification). If N_2O makes up 10 per cent of the volatilised nitrogen, 2 kg N_2O-N would be generated in the primary cycle. Assessments of fertiliser effects on N_2O emissions usually stop at this point even though only 20 of the 100 kg N have been returned to the atmosphere and it can be reasonably assumed that almost all would be returned within a few years. Secondary flows include feeding of the 50 kg of harvested nitrogen to animals, which generate 45 kg of excreta nitrogen. The excreta is returned to cropland to fertilise a second crop. However, about half of this nitrogen is volatilised as ammonia (NH_3) prior to or during excreta application.

Volatilised NH_3 is dispersed aerially, and subsequently returns to and cycles through both natural ecosystems and cropland. Ammonia volatilisation from agricultural systems is globally important (Isermann, 1992) but its impact on N_2O emissions has not been explicitly addressed. To provide some perspective, it should be noted that the quantities of fertiliser nitrogen used and animal excreta N generated by USA agriculture are equal (Bouldin et al., 1984). On a global basis, about 30 of the 80 Tg fertiliser N used each year are volatilised as NH_3.

Similarly, the amount of N_2O arising from leached nitrate, which may average 20-25 per cent of applied nitrogen (Meisinger and Randall, 1991), is not known but much may be denitrified in riparian zones or cycled through wetland or aquatic vegetation. A complete accounting of fertiliser nitrogen, biologically fixed nitrogen, and nitrogen mineralised from soil organic matter is difficult to achieve, but needed if we are to accurately assess the impact of increased use of nitrogen in agricultural ecosystems on terrestrial N_2O emissions (Duxbury et al., 1993).

3 The Working Group felt that considering only N_2O emissions from cultivated agricultural soils was too narrow a view. The whole picture of anthropogenic effects of N_2O emissions should include the indirect fertilisation of grasslands, forests and wetlands from agricultural and industrial sources. Since cultivated lands represent only about 13 per cent of the global land surface it does not seem appropriate to consider only those areas when estimating global N_2O emissions.

Calculations of nitrogen additions and N cycling within all of these ecosystems must include nitrogen from atmospheric deposition and nitrogen from soil organic matter mineralisation. The entire calendar year should be considered, not just the cropping season.

Improving methodology for estimating N_2O emissions may evolve in a series of steps, beginning with the above equations and ending with development of process based models which are used to develop regional and larger scale emission models. With these models, if a relatively simple set of input information can be developed, then detailed emission calculations may be made. Because of the inherent spatial and temporal variability associated with N_2O production and emissions from soils, it appears that very simple approaches will not provide realistic emission estimates.

4 CO_2 emissions from peat compost should be identified as an area for future work if the expert group believes that these emissions are sufficient in quantity to warrant inclusion in the methodology, and that adequate data are available to allow their estimation.

To support the development of the steps for improved methodology for calculating country-wide N_2O emissions, a number of unknowns were identified. Better understanding of these issues should improve methodologies.

AGRICULTURE

Recommendations:

- a Perform measurements in important tropical agricultural systems.
- b Estimate anthropogenic nitrogen input into "natural systems" and amount processed into N_2O.
- c Develop process level models, based on field research measurements, refine and test the models and use these models as basis for developing regional and larger scale emission models.

4.6 References

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5 LAND USE CHANGE & FORESTRY

1 Overview

This chapter summarises methods for calculating greenhouse gas (GHG) emissions from human activities which:

1. change the way land is used (e.g., clearing of forests for agricultural use, including open burning of cleared biomass), or
2. affect the amount of biomass in existing biomass stocks (e.g., forests, village trees, woody savannas, etc.).

The biosphere is a strong determinant of the chemical composition of the atmosphere. This has been true since the existence of the biosphere, and hence well before the presence of humans. A rich variety of carbon, nitrogen, and sulphur gases are emitted and absorbed by the biosphere. There is, however, strong evidence that the expanding human use and alteration of the biosphere for essential food, fuel and fibre is contributing to increasing atmospheric concentrations of greenhouse gases. The dominant gas of concern in this source category is carbon dioxide (CO_2), and much of the methodology discussion in this chapter is specific to CO_2. Other important direct greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O), and indirect greenhouse gases,[1] including carbon monoxide (CO), oxides of nitrogen (NO_x, i.e., NO and NO_2), and non-methane volatile organic compounds (NMVOCs) are also produced from land use change and forest management activities, particularly where burning is involved. Non-methane volatile organic compounds are emitted in significant quantities from biomass burning. These emissions could be estimated using the same approach provided for other non-CO_2 gases. However, the detailed methods and default information have not yet been developed and included in this version of the *Guidelines*. This is an area to be considered in future improvements to the *Guidelines*. Estimates of carbon dioxide emissions due to land use change vary considerably.

Estimates vary due to uncertainties in annual forest clearing rates, the fate of the land that is cleared, the amounts of biomass (and hence carbon) contained in different ecosystems, and the carbon released when soils are disturbed. The 1990 IPCC Scientific Assessment estimated the flux due to tropical deforestation in 1980 to be 0.6-2.5 Pg CO_2 expressed in terms of mass of carbon (CO_2-C), and estimated the average annual emissions for the decade 1980-1989 to be 1.6±1.0 Pg CO_2-C. Subsequently, the IPCC (1992) reviewed more recent but still uncertain information, and could find no basis for changing the earlier estimate. Carbon sequestration by tropical tree plantations was not explicitly included in these estimates but is thought to be relatively small: in 1980 these plantations were estimated to absorb only 0.03-0.11 Pg CO_2-C (Brown et al., 1986). At the time of the IPCC 1990 Assessment, estimates in the literature indicated the net release or uptake of CO_2 due to land use change in the temperate and boreal regions in the 1980s to be small with CO_2 emissions from deforestation in these regions almost balanced by CO_2 uptake from the regrowth of forests (Houghton et al., 1987; Melillo et al., 1988). More recently, several analyses have suggested that growth of existing forests in temperate and boreal regions may be a significant carbon sink, potentially as much as 1.0 Pg C annually. Analysts have suggested a number of complementary factors which could be causing these sinks, including regrowth of historically cleared forests, CO_2 fertilisation, and nitrogen fertilisation due to atmospheric deposition (e.g., Tans et al., 1990; IPCC, 1992; and Kauppi et al., 1992). The most recent IPCC (1994) publication on this subject estimates that normal regrowth of forests in the Northern Hemisphere results in an annual sink of 0.5 +/- 0.5 GtC. Based upon the latest estimates of CO_2 sources, sinks and atmospheric storage, the IPCC (1994) estimates a remaining terrestrial sink of 1.4 +/- 1.5 GtC/year. This apparent imbalance in the carbon budget, which was previously referred to as a "missing sink," is believed to be due to CO_2 fertilisation, N fertilisation, climate change (e.g., temperature increase) and possibly other factors.[2] The precise mix and relative contribution of these processes to the remaining terrestrial sink is still a subject of research and debate.

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[1] "Indirect" greenhouse gases here refers to gases which contribute to the chemical formation or destruction of ozone (O_3) in the atmosphere. As O_3 is an important greenhouse gas, the gases which create or destroy it affect the radiative forcing of the atmosphere indirectly.

Gross emissions of non-CO_2 trace gases (CH_4, CO, N_2O, and NO_x) due to biomass burning are also net emissions and are generally produced immediately, while gross emissions of CO_2 due to reductions in forest area may or may not be balanced by uptake of CO_2 and may occur over immediate or delayed time frames.[3] Similarly, increases in forest area or in the biomass density of existing forests will result in CO_2 uptake at varying rates and over delayed time frames. Only about 50-60 per cent of the carbon estimated to have been released in 1980 was a result of deforestation in that year. The remainder was a release due to oxidation of biomass cleared in previous years (Houghton, 1991). Other land use changes, such as land flooding, result in continuous greenhouse gas emissions for as long as the land remains in its altered state.

5.1.1 Background - Biomass Stocks and Carbon Fluxes

Vegetation withdraws carbon dioxide from the atmosphere through the process of photosynthesis. Carbon dioxide is returned to the atmosphere by the (autotrophic) respiration of the vegetation and the decay (heterotrophic respiration) of organic matter in soils and litter. The gross fluxes are large; roughly a seventh of the total atmospheric carbon dioxide passes into vegetation each year (on the order of 100 Pg CO_2-C per year), and in the absence of significant human disturbance, this large flux of CO_2 from the atmosphere to the terrestrial biosphere is balanced by the return respiration fluxes. This remarkable balance is clearly expressed by the relative constancy, which can be inferred from the ice core records, of the concentration of atmospheric CO_2 between 10th and 18th century.

Land use change and the use of forests directly alters these fluxes (and their balance) and consequently the amount of carbon stored in living vegetation, litter, and soils. For example, forest clearing for agriculture by burning greatly increases the return (respiration) flux of CO_2 and decreases for a while the photosynthetic flux. Burning is, after all, simply a rapid form of oxidation or decay. Subsequently, the CO_2 flux of the cleared area will equilibrate: the photosynthesis associated with the agricultural production being balanced by the respiration of the vegetation, the decay of on-site organic material, and the oxidation of the agricultural product when it is consumed, perhaps off site. However, the total amount of carbon stored in the terrestrial system will have been reduced because a forest contains more carbon than does a corn field, and the removed carbon (i.e., the forest) was not put into long term storage pools. An obvious consequence is that the activity resulted in a net flux of CO_2 from the land and vegetation to the atmosphere. A natural first order assumption is that the net reduction in carbon stocks is equal to the net CO_2 flux from the cleared area.

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[2] For recent analyses of the effects of changing CO_2 concentrations and climate variables on terrestrial sinks, see Mellilo et al., 1993, Smith and Shuggart, 1993, Cramer and Solomon, 1993, Kokorin and Nazarov, 1994 and Alcamo et al., 1994. For analysis of the possible effects of N fertilisation from atmospheric deposition, see Gifford, 1994, Rastetter et al., 1992 and Comins and McMurtrie, 1993. It is also possible that atmospheric deposition of air pollutants can damage forests, as discussed in Denniston, 1993, which would reduce the amount of carbon stored in forests. However, it is uncertain whether or not this is a significant effect at global or national scales.

[3] Delayed releases of non-CO_2 trace gases are an important research issue. These releases may be important , but are currently too uncertain to be included in calculations.

Forest harvest does not necessarily result in a net flux to the atmosphere. It can produce a complex pattern of net fluxes that change direction over time. For instance, suppose that a forest is harvested, producing wood products and leaving some slash and debris. Initially, the CO_2 flux from the wood products that decay rapidly, plus the increased respiration flux of CO_2 associated with the oxidation of the slash (in effect the litter pool has been increased and hence so has the respiration flux associated with this pool), could be greater than the flux from the atmosphere due to the photosynthesis and the resulting carbon storage in the regrowing forest. Consequently, there is a net flux of CO_2 from the forest and soil to the atmosphere. This would also be reflected in the carbon accounting: the amount of carbon in the original living vegetation, the litter, and the soils would be greater than the amount of carbon in the young regrowing forests, litter, soils and forest products pool. However, if some of the forest products are very long-lived, and if the forest regrows to its original level, then the integrated net flux must have been from the atmosphere to the terrestrial biosphere since the resulting total terrestrial carbon stocks (vegetation, litter, soils, and wood products) would be greater than before the forest harvest.

This characteristic, that changes in land use today affect both present and future CO_2 fluxes associated with that specific land use, is one feature of CO_2 emissions analysis that distinguishes land use from fossil fuel consumption. Consequently, when one considers the issue of CO_2 flux associated with land use today or in any base year, one must consider past land use activities and their effects upon current fluxes of CO_2. Box 1 provides some illustrative numerical examples of carbon fluxes associated with land use change over a series of years.

BOX I
ILLUSTRATIVE CALCULATIONS OF CARBON FLUXES

Consider the example of forest clearing for agriculture which results in a net flux to the atmosphere. For descriptive purposes we consider the following assumptions:

1) a 20 year time frame (e.g., 1970 to 1990),
2) one hectare is cleared each year (so that over the 20 year period, 20 hectares are cleared),
3) cleared land is used as pasture, which is established the year following the clearing,
4) after three years cleared land is abandoned and it regrows linearly to 75 per cent its original biomass in 15 years but no further,
5) all of the vegetation is completely burned at the time of clearing and there are essentially no soil or litter pools, and
6) there are 200 tonnes of carbon per hectare in the forest biomass and 5 tonnes carbon per hectare in the pasture.

In the first year, there is a 200 tonne *net* flux of carbon as CO_2 to the atmosphere. In the second there is a 195 tonne *net* flux; the clearing of the second hectare is partially balanced by the establishment of the first pasture. In the third, there is a *net* flux again of 195; the clearing of the third hectare is again partially balanced by the establishment of the second pasture; however, the first pasture is now again in a steady state (as a pasture). The fourth year the pattern is again the same, but in the fifth year the net annual flux drops to 185 as the first pasture is now abandoned and begins to recover to a secondary forest. In the sixth year, the flux drops to 175 as two hectares are recovering to a secondary forest. In this example, in 1989 one hectare would be converted to pasture (200 tonne flux of carbon to the atmosphere), one hectare would have become a pasture (5 tonne flux to the terrestrial biosphere), two hectares would be in steady state as pasture, and 15 hectares would be recovering to secondary forest with one hectare in its final year of recovery (150 tonne flux to the terrestrial biosphere). The 1989 gross flux of carbon from land clearing in 1989 would still be 200 tonnes to the atmosphere, but the net flux to the atmosphere in 1989 associated with land clearing would be 45 tonnes of carbon as CO_2. The 1990 flux would be the same since now the original one hectare of pasture would have reached a new steady state as a secondary forest.

Many variations on this example can be devised: e.g., conversion of some vegetation to charcoal, varying deforestation and regrowth rates. For instance, if the land clearing rates declined over the time period, the 1990 net flux could easily be from the atmosphere to the biosphere even though the net integrated flux over the time period was to the atmosphere.

There are other complexities such as the variety of land-use practices, different assumptions about biomass densities, recovery rates, the dynamics of the associated litter and soil pools, and so forth. However, the net flux to or from a particular site will always be reflected in the change of carbon stocks on site and/or in the products pools associated with the site. Thus, a methodology that determines carbon stock changes also provides estimates of the net fluxes of CO_2.

5.1.2 The Proposed Approach

The fundamental basis for the methodology rests upon two linked themes: i) the flux of CO_2 to or from the atmosphere are assumed to be equal to changes in carbon stocks in existing biomass and soils, and ii) changes in carbon stocks can be estimated by first establishing rates of change in land use and then applying simple assumptions about the biological response to a given land use. As noted above, there are large uncertainties in all current methods for estimating fluxes of CO_2 from forestry and land use change. *Direct* measurements of changes in carbon stocks are extremely difficult since one must confront the difficulty of determining small differences in large numbers as well as the inherent heterogeneity of terrestrial systems. A more practical first order approach in many countries is to make simple assumptions about the effects of land use change on carbon stocks and the subsequent biological response to the land use change, and to use these assumptions to calculate carbon stock changes and hence the CO_2 flux. This observation is at the heart of the proposed approach. It is also central to more complex terrestrial carbon accounting models (e.g., Moore et al, 1981; Houghton et al., 1983 and 1986; Melillo et al., 1988; and Emanuel et al., 1992).

Rates of change of land use are difficult to establish, although there are a variety of data on which to base land use change estimates. The Technical Appendix to this chapter reviews sources of data on rates of tropical deforestation, the land use change which currently makes the largest contribution to CO_2 flux. Finally, the assumptions regarding the response of vegetation and soils to different land uses and land use change can be expressed in simple terms which can be altered for specific conditions in different countries or regions.

The methodology is designed to be comprehensive, i.e., to cover all of the main land use change and forestry activities; and to be feasible to implement by all participating countries. It can be implemented at several different levels of complexity and geographic scales, depending on the needs and capabilities of national experts in different countries.

1. A simple, first order approach can be based on very aggregate default data and assumptions, derived from the technical literature, and provided throughout the text. Methods are presented in the context of national level aggregate calculations for a limited set of subcategories which can be supported by these default values. It is important to note that many of the default data provided in the land use change and forestry chapter are highly uncertain. Many of the important values needed for the calculations are not well established or are highly variable from region to region, or within very small subregions within a given country. In many cases in which values are particularly uncertain (e.g., the fraction of cleared biomass burned on site), these weaknesses are discussed in the text. Where global average values are highly uncertain, they can be used for first order calculations or for comparison, but probably do not provide a basis for a credible final inventory. National experts in forestry and related fields should be consulted to determine the most appropriate values for use in national inventories.

2. A more accurate level can be achieved simply by substituting country-specific values for general defaults provided in the methodology. If appropriate and possible, locally available data can be used to carry out calculations at a more detailed geographic scale and/or subcategory level. Alternative levels of detail are discussed more fully in the next section. National experts are strongly encouraged to substitute more appropriate (i.e., country- or region-specific) and more detailed input data wherever they are available.

3. Forest inventory data can also be used with this methodology. It is important to note that some countries with highly developed forestry industries do in fact keep

track of existing commercial forests through periodic detailed surveys. In these countries it is generally the ongoing management of existing forests rather than land use changes which has the greatest impact on GHG emissions or removals. National experts who have very detailed, inventory based data, can reformat and analyse these data to derive equivalent average responses (e.g., annual biomass growth rates by ecosystem type) which can be aggregated up to categories matching the simple approach outlined here. This procedure is discussed in more detail in the *changes in forest and other woody biomass stocks* section below.

The intent is to provide a calculation and reporting framework which can accommodate users with vastly different levels of available data, yet allow them all to present the results on a comparable basis.

5.1.3 Priority Categories

In estimating the effects of land use and land use changes on the concentration of greenhouse gases, it is reasonable to stage the calculation methods so that the most important components can be addressed first, and complexities and subtleties of the relationship of forestry and land use change to fluxes of CO_2 and other gases can be incorporated in a consistent manner into subsequent calculations as knowledge advances and data improve. The methodology presented in this chapter focuses initially on a simple, practical, and fair procedure for determining the carbon dioxide flux directly attributed to forest management and land use change activities. This procedure must also account for the influence of past land use changes upon the contemporary CO_2 flux,[4] as well as trace gas emissions from biomass burning where this occurs in conjunction with land use change.[5]

On a global scale, the most important land use changes that result in CO_2 emissions and removals are:

- **changes in forest and other woody biomass stocks** - the most important effects of human interactions with existing forests are considered in a single broad category, which includes commercial management and logging for forest products, the harvest of fuel wood, and establishment and operation of forest plantations as well as planting of trees in urban, village and other non-forest locations;[6]
- **forest and grassland conversion** - the conversion of forests and grasslands to pasture, cropland or other managed uses can significantly change carbon stored aboveground and in soils;[7]
- **abandonment of managed lands** which regrow into their prior natural grassland or forest conditions;

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[4] Similarly, current land-use changes will affect future fluxes of carbon dioxide.

[5] Burning of biomass residues can occur in other situations which are not land use change, e.g., in the utilization of forests or other biomass stocks as a part of the ongoing management of these stocks without changing the land use. This should be treated in the same way as burning of cleared forests for calculation of non-CO_2 GHG from burning.

[6] Changes in forest and other woody biomass stocks are accounted for on a year to year basis.

[7] Conversion of forests is also referred to as "deforestation" and it is frequently accompanied by burning.

The method also addresses the immediate release of non-CO_2 trace gases (CH_4, CO, N_2O and NO_x) from the open burning of biomass from forest clearing. The approach is essentially the same as that used for non-CO_2 trace gases from all burning of unprocessed biomass, such as burning of traditional biomass fuels (Chapter 1: Energy), and burning of agricultural residues and savanna burning (Chapter 4: Agriculture). These calculations are similar to fossil fuel emission calculations, in that they do not include time lags and all emissions are *net* emissions.

5.1.4 Relationships Among Categories

It is possible that some areas of land can fit the definitions of two categories - e.g., abandoned lands regrowing and changes in woody biomass stocks - simultaneously. In this situation, the most recent, significant human interaction should be used to allocate land into categories. Even though an area may have been abandoned and allowed to regrow, if it subsequently begins to be "managed" (e.g., as a significant source of fuelwood) it should be reclassified in the *changes in forest and other woody biomass stocks* category.[8] It is important to recognise some key linkages and interactions both among components of the land use change and forestry methods and with other calculations discussed in other chapters. Figure 5-1 illustrates a number of complicated relationships among these categories and also with biomass fuel combustion which is covered in the energy source category. Key linkages which should be understood are:

1 To estimate CO_2 emissions from *burning of cleared forests*, it is only necessary to know the total amount of biomass which is burned in the inventory year.

2 However, it is necessary to divide this burning into on-site and off-site (fuelwood) portions for two reasons:

   First, the type of burning affects the emissions of non-CO_2 trace gases such as methane so that different emission factors may be applied to open burning on-site and to fuelwood use off-site.

   Secondly, the amount of fuelwood removed from cleared forests must be deducted from total fuelwood consumed for the nation or region to determine the residual amount of fuelwood which must have been harvested from forest and other woody biomass stocks. This is only an issue for those countries which must infer some or all of forest harvest from wood consumption surveys. If some of the fuelwood consumed has already been accounted for once in calculations of forest clearing, this amount must be taken out of the amount attributed to managed forests.

3 Fuelwood Consumption Information. Countries which have accurate and complete statistics on direct harvesting of all types of wood from biomass stocks, and all uses of biomass for fuel, should use locally available data. Many countries, however, have significant amounts of wood removed from forests, primarily for domestic fuel use, which are not accounted for in commercial harvest statistics. For these countries, an optional Fuelwood Consumption Accounting approach is provided. This approach is based on household and other fuel consumption surveys, scaled to population to estimate total annual demand for fuelwood and other fuels. This information can then be used instead of, or in combination with, commercial harvest and sales statistics.

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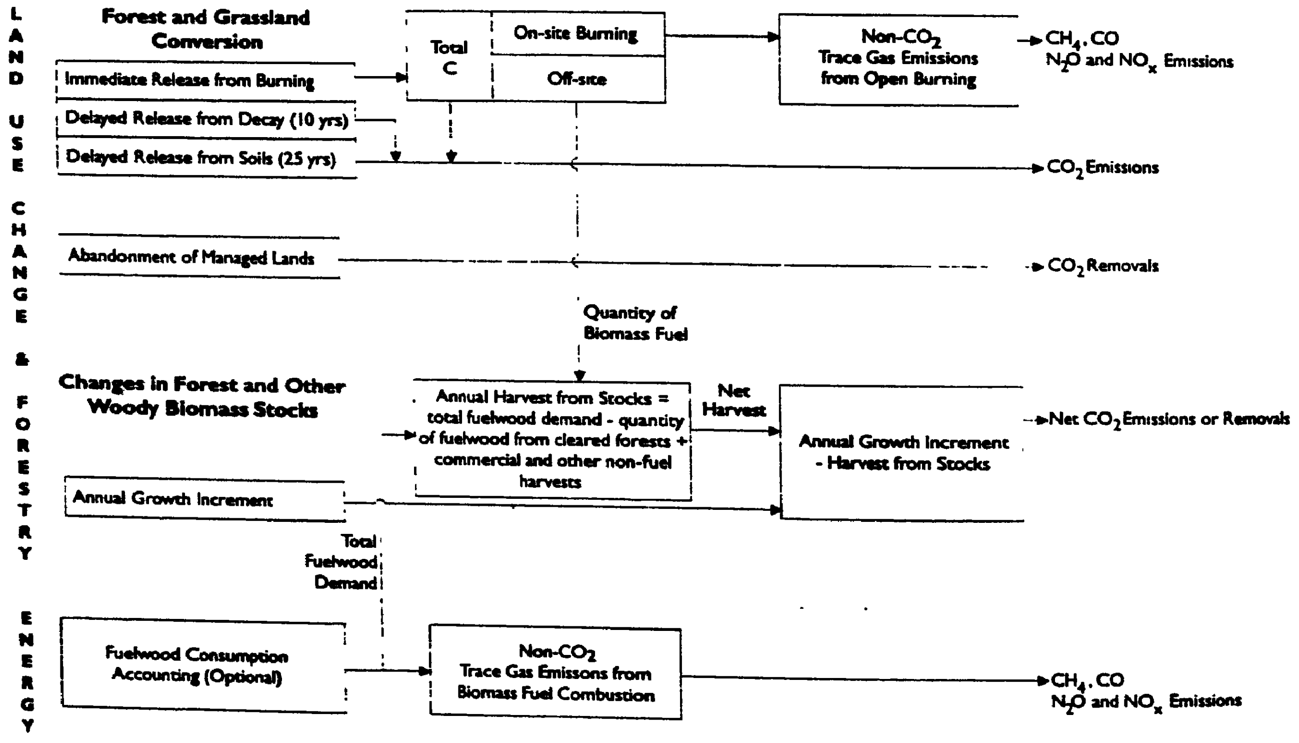
[8] One problem that has been pointed out with this procedure, is that it may lose track of some accumulation of soil carbon where the lands have been abandoned after long agricultural use. More detailed treatment of soil carbon changes due to both agricultural and forest management practices has been identified as a priority for future work.

Fuelwood consumption information is used in two ways:

- for estimating non-CO_2 trace gas emissions from biomass fuel combustion (in the energy section of the methodology); and
- total wood consumption, corrected to deduct any wood which has come from forest clearing (for which CO_2 is already accounted), is also a key input to the calculations of net CO_2 emissions or removals from *changes in forest and other woody biomass stocks.*

FIGURE 5-1: Relationships Among Categories


LAND USE CHANGE & FORESTRY
Forest and Grassland Conversion
Immediate Release from Burning
Delayed Release from Decay (10 yrs)
Delayed Release from Soils (25 yrs)
Total C
On-site Burning
Off-site
Non-CO2 Trace Gas Emissions from Open Burning
CH4, CO N2O and NOx Emissions
CO2 Emissions
Abandonment of Managed Lands
CO2 Removals
Quantity of Biomass Fuel
Changes in Forest and Other Woody Biomass Stocks
Annual Harvest from Stocks = total fuelwood demand - quantity of fuelwood from cleared forests + commercial and other non-fuel harvests
Net Harvest
Annual Growth Increment - Harvest from Stocks
Net CO2 Emissions or Removals
Annual Growth Increment
Total Fuelwood Demand
ENERGY
Fuelwood Consumption Accounting (Optional)
Non-CO2 Trace Gas Emissons from Biomass Fuel Combustion
CH4, CO N2O and NOx Emissions

Box 2
FOREST AND GRASSLAND CATEGORIES

Ecosystem categories have been established for land use change and forestry calculations based on conventions common in the specialised literature including studies which provide average values which can be used as 'defaults. These categories are consistent with the tables of default values provided, and are used in the simple calculations presented in the *Workbook*. National experts are free, indeed encouraged, to use more detailed characterisations of ecosystems in their countries if the data are available and differences are important for carbon calculations. If more detailed categories are used, however, it is necessary to aggregate these up to match the broad specified categories in order to ensure consistency and comparability with national data across all participating countries. The categories are arranged hierarchically as follows:

Ecosystem Types

Tropical Systems

Forests	Moist Seasonal Dry (including woody savannas)
Grasslands	

Temperate

Forests	Deciduous Evergreens
Grasslands	

Boreal Forests

Within each ecosystem category, subdivisions are recommended where applicable, based on historic usage patterns. These **Usage Categories** are:

Moist - These are evergreen dense forests which receive significant rainfall evenly throughout the year (i.e., there is not a distinct wet and dry season). Rainfall in these forests is 2000 mm per year or more.

Seasonal - Semi-deciduous forests with a distinct wet and dry season and rainfall between 1200 and 2000 mm per year.

Dry Forests - Generally consistent with the definition of open forests in previous documents. Less than 1200 mm rainfall per year.

Primary - Generally applied to forests which are in or close to a natural, undisturbed state.

Secondary - Forests which have been logged, or cleared for other purposes, and are regrowing, but are not fully regrown. These forests would be expected to have significantly lower biomass densities than undisturbed forests of the same type.

Protected - It may be important for some countries to track separately forests or grasslands which have been designated as national parks or in other ways legally protected.

Degraded - Where forests or grasslands have been overutilised or poorly managed historically, they may have substantially reduced biomass densities.

5.1.5 Chapter Organisation

The remainder of this chapter presents methods for calculating greenhouse gases from land use change and forestry in two stages. The next section, *Basic Calculations*, presents initial simple calculations for each of three broad categories of land uses and changes in land use identified above. These categories also correspond directly to the subsections of the Land Use Change and Forestry Module of *Volume 2: Workbook*.

The second stage, *Refinements in Calculations*, discusses a range of complexities and refinements which ideally could be included in such calculations, as data and understanding permit, in order to improve accuracy and completeness. These possible refinements include more detailed treatment of some aspects of the basic categories of land uses and land use changes, as well as additional categories, which can affect carbon stocks and are potentially important for other greenhouse gases. Issues discussed include the delayed release (or uptake) of non-CO_2 trace gases after burning of forests (either as a prescribed forest management tool or as a means of land-clearing), forest degradation, traditional shifting cultivation, and conversion of wetlands to other land uses or the reverse. These activities and other refinements can be incorporated in more detailed versions of the calculations.

A *Technical Appendix*, as mentioned, is also provided, which deals with sources of information on rates of land use change, a critical activity data input for calculating GHG emissions.

5.2 Basic Calculations

5.2.1 Introduction

The basic calculations focus primarily on the land use changes and land use activities that result in the largest, potential flux of CO_2 to the atmosphere or have the largest potential for sequestering carbon.

Two categories of land use change are considered:

- forest and grassland conversion to agricultural lands
- abandonment of managed lands

In contrast to other aspects of the greenhouse gas emissions methodology, the estimation of CO_2 from land use change requires the consideration of events over a long period of time. When forests are cleared or agricultural lands abandoned, the biological responses result in "commitments" of fluxes of carbon to or from the atmosphere for many years after the land use change. This methodology is designed to produce an emissions estimate that is comparable to other elements of the inventory, fossil fuel emissions, for example. That is, it attempts to quantify the flux to or from the atmosphere *in the inventory year*. To do this, it is necessary to obtain estimates of land use change activities for many years prior to the inventory year, and estimate the effects of these activities on the current year fluxes. The two selected categories are considered to be the most important land use changes affecting CO_2 fluxes, but are not a comprehensive set. Many relevant land use changes are excluded from the basic calculations. These are discussed in the last section of this chapter.

Relevant forestry (on-going land use) activity is combined in one very broad category, *changes in forest and other woody biomass stocks*, which is defined here to include potentially a wide variety of land use practices. Key examples are establishing and harvesting plantations, commercial forest management and harvesting, and fuelwood gathering.

Conceptually, this category is intended to account for all significant human interactions with forests and other woody biomass stocks which affect CO_2 fluxes to and from the atmosphere, but which do not result in a land use change. It is intended to account, at least on a crude level, for all existing forests, with two exceptions.

1 Natural, undisturbed forests, are not considered to be either an anthropogenic source or sink, and are excluded from the calculations entirely.

2 Forests regrowing naturally on abandoned lands are a net carbon sink attributable to past human activities and are accounted for separately. "Abandoned" lands are by definition assumed not to be subject to ongoing human intervention (of significance to carbon stocks) after abandonment.[9]

NOTE: Forests classified as natural, or abandoned / regrowing, can be excluded from the woody biomass stocks accounting only if there is no significant current human interaction with these forests. If they are being used as a source of fuelwood, or are being affected in other ways by ongoing human activities they should be accounted for on an annual basis as part of *changes in forest and other woody biomass stocks*. In many countries lands which are classified as natural or abandoned, are in fact harvested informally. Thus, in some countries or regions with fuelwood shortages, little forest will actually fall into the natural or abandoned categories.

Several simplifying assumptions are made in the basic calculation methodology. A number of refinements are possible to improve on these basic calculations. One important option is to implement the basic calculations at a more detailed level of subcategories or geographic detail. National experts are strongly encouraged to do so if data are available. Box 3 discusses possibilities for adapting the methodology to various levels of detail, depending on the capabilities and data available to the user, and the relative importance of various components to the individual country.

Other possibilities for improving the accuracy and completeness of the basic calculations are possible. For example, the fate and amount of belowground biomass (roots, etc.) is currently ignored in the calculation. The section entitled *Refinements to Calculations*, later in this chapter, reviews a number of possible additions and refinements.

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[9] Abandoned lands which are regrowing naturally may be cleared again. In this case, they should shift again to cleared lands, probably with a lower value for preclearing biomass density than when they were first cleared.

BOX 3
ALTERNATIVE LEVELS OF DETAIL

For simplicity and clarity, this chapter discusses calculation of emissions at a national level and for a relatively small number of subcategories within each category of land use change and forestry. The level of detail in the subcategories is designed to match the available sources of default input data, carbon contents and other assumptions. It is important, however, for users of these emissions methodology guidelines to understand that they are not only permitted but encouraged to carry out the GHG emissions inventory calculations at a finer level of detail, if possible. Many countries have more detailed information available about land use change, forests and agriculture, than was used in constructing default values here. It may be important in such countries to carry out emissions calculations at finer levels in two ways:

1 **Geographic detail at a regional, rather than a national level**

If data are available, experts may find that GHG estimation for various regions within a country are necessary to capture important geographic variations in ecosystem types, biomass densities, fractions of cleared biomass which are burned, etc.

2 **Finer detail by subcategory**

If data are available, experts may subdivide the recommended activity categories and subcategories to reflect important differences in ecology or species, land use or agricultural practices, bioenergy consumption patterns, etc.

In all cases, working at finer levels of disaggregation does not change the basic nature of the calculations, although additional data and assumptions will generally be required beyond the defaults provided in the chapter. Once GHG emissions have been calculated at whatever is determined by the national experts to be the most appropriate level of detail, results should also be aggregated up to the national level and the standard categories requested in the IPCC proposed methodology. This will allow for comparability of results among all participating countries. Generally, the data and assumptions used for finer levels of detail should also be reported to the IPCC to ensure transparency and replicability of methods. *Volume 1: Reporting Instructions* discusses these issues in more detail.

5.2.2 Changes in Forest and Other Woody Biomass Stocks

The category *changes in forest and other woody biomass stocks* as used in these basic calculations is very broad, potentially including a wide variety of land use practices. This discussion focuses heavily on changes in forests, which globally account for the largest component of annual changes in biomass stocks. However, other types of biomass such as non-forest trees (e.g., in villages, cities, etc.) and woody shrubs in grasslands should be included when they are a significant component of total changes in biomass stocks, as is likely to be the case for some specific countries. A basic organising concept in this chapter is that all existing forests can be allocated into one of three categories.

1 Natural, undisturbed forests, where they still exist and are in equilibrium, should not be considered either an anthropogenic source or sink. They can therefore be excluded from national inventory calculations.

NOTE: Many countries may have little or no forests or woody biomass stocks which are not affected significantly by humans. In areas with severe fuelwood shortages, for example, significant biomass - and hence carbon - may be removed for fuel annually even from "natural forests" and abandoned lands.[10]

2 Forests regrowing naturally on abandoned lands are a net carbon sink attributable to past human activities and are accounted for as discussed in a later section. While the current regrowth is considered a response to past anthropogenic activity, "abandoned" lands are by definition assumed not to be subject to ongoing human intervention (of significance to carbon stocks) after abandonment.

3 All other types of forest are included in the changes in forest and other woody biomass stocks category. That is, any forest which experiences periodic or on-going human interventions that affect carbon stocks should be included here. In the basic calculations, the chapter focuses primarily on a few types of human interactions with forests which are believed to result in the most significant fluxes of carbon. National experts are encouraged, however, to estimate emissions for any activity related to existing forests which is considered to result in significant carbon emissions or removals, and for which necessary data are available. Any such activities falling within our broad definition of *changes in forests and other woody biomass stocks* should be included in this category and reported to the IPCC as discussed in *Volume 1: Reporting Instructions*.

Some of the activities in the changes in forest and other woody biomass stocks category which can potentially produce significant carbon fluxes are:

- management of commercial forests - including logging, restocking, selective thinning, etc., as practised by commercial forest products industries
- establishment and management of commercial plantations[11]
- other afforestation, and reforestation programmes
- informal fuelwood gathering

This category also includes trees which may not traditionally be considered part of "forests". It can include village and farm trees if these are important for biomass and biofuel accounting in some developing countries. It can also include urban trees, trees planted along highways, aircraft runways, etc., if these are considered significant for a particular country's biomass calculations. These dispersed trees do not contribute greatly to carbon fluxes to or from the atmosphere on a global scale. However, in some countries, they may be important in accounting for the total amount of wood used for fuel. Also, they may be of interest to some countries because of their potential use in response strategies. For these reasons, they are included in the basic calculation methods. National experts who feel they are important, and have the necessary locally available data, can include them.

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[10] Also, as discussed in the chapter introduction, there are likely to be widespread human induced effects, e.g., CO_2 fertilisation and nitrogen deposition, which cause changes in virtually all terrestrial biological systems. In this sense, there may be no natural forests which are not subject to human induced GHG emissions or removals. However, at present, the understanding of these broad effects is so uncertain, and quantitative estimation so difficult, that they are not included in the basic calculations recommended for all national inventories.

[11] Plantations are forest stands that have been established artificially, to produce a forest product "crop". They are either on lands that previously have not supported forests for more than 50 years (afforestation), or on lands that have supported forests within the last 50 years and where the original crop has been replaced with a different one (reforestation) (Brown et al., 1986).

In addition to trees in non-forest locations, in some countries, woody biomass from shrubs or other plants, in grasslands or other locations, may play a significant role in total fuelwood supply. If this is the case, the annual supply of biomass from these "non-trees" must be included in the overall fuelwood accounting. Otherwise the loss of biomass stocks in forests may be overstated.

As illustrated in the above list, the changes in forest and other woody biomass stocks category includes some tree planting activities which, strictly speaking, are land use changes. Plantation establishment and other afforestation/reforestation programmes are examples. It is recognised that this is conceptually inconsistent as the category is intended to account for ongoing interactions with existing forests. However, from a pragmatic perspective, including these activities within the category can simplify the calculations. These subcategories are land use changes which create new forest stocks. As soon as the land use change occurs (i.e., the tree planting), the new land use becomes part of the *changes in forest and other woody biomass stocks* category which is accounted for on an annual incremental basis. Although it would be possible, it is not necessary to estimate the lagged effects of this change as is done with other land use changes.[12] While including such a range of tree-related activities in one category may introduce some confusion, the calculation procedure is basically the same for all subcategories, and this allows the simplest possible set of emissions calculations.

As discussed above, if lands previously considered abandoned and regrowing, or natural forests, are being affected by human activity in the inventory year, they should be reclassified into the *changes in forest and other woody biomass stocks* category.

As discussed in the *Overview*, the methodology is designed to accommodate users at several levels of detail. This is especially important in the managed forests category. Possible levels include:

1 A simple first order approach, covering the main subcategories, with calculations based on simple default assumptions and default data provided.

NOTE: An inventory of land use change and forestry emissions developed on default values only is unlikely to be considered credible for any country which has significant emissions or activities in these areas.

2 Calculations at the same level of detail but substituting more appropriate data and assumptions from local sources.

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[12] There is one omission in this accounting which may be important for some countries. If plantations are established on previously unforested lands, there may be a long term accumulation of carbon in the soil as a result of the land use change. This would not normally be picked up in the simple *changes in forest and other woody biomass stocks* calculations. It could be added if national experts have detailed data on the pre-plantation land uses, the soil carbon contents and rates of accumulation, etc.

3. Calculations following the same structure, but broken down to finer levels of detail to improve accuracy and utility of estimates, where locally available data can support this.
4. Estimates derived from much more detailed and precise inventory-based forest accounting methods. These results can be reformatted and presented in the form of calculations comparable to those used by the other national experts operating with less detailed data.

It is highly desirable that the methodology be relevant for countries which have access to much more detailed data on changes in forest stocks. Some countries with highly developed forestry industries do in fact keep track of existing commercial forests through periodic detailed surveys. For such countries, it is possible to derive from survey results aggregate values comparable to the data and assumptions used in the simple approach, and present them in this common format. This will assist all interested parties in evaluating various national estimates on a comparable basis, and will thus be necessary to comply with requirements of *Volume I: Reporting Instructions*. Box 4 provides some further discussion of these procedures.

BOX 4

ADAPTING DETAILED FOREST INVENTORY DATA TO THE IPCC FORMAT

A number of countries with highly developed commercial forestry industries routinely collect forest biomass data at a detailed inventory level which allows for relatively precise and direct assessment of the changes in biomass stocks, and equivalent carbon fluxes. National experts working with data of this kind should be able to derive from it values equivalent to those used in calculating emissions with the IPCC methodology.

Regardless of how detailed the data base used may be, the results ultimately must be presented in units (e.g. Gg) of carbon and CO_2 emitted or removed in a given average response category (e.g., annual biomass growth rates by ecosystem type). Similarly, the number of hectares of forest in various types can be aggregated up to categories matching the simple approach outlined here. The amount of biomass removed as commercial harvest or for other reasons, should also be relatively well established in such inventories. With these data, it should be possible to, in effect, work backwards to derive the necessary input assumptions and aggregate values. For example, national experts might start with a change in total biomass for specified forest types (and/or regions) over a specified time period. Then they could add the amounts of biomass removed through commercial harvest or for other reasons (e.g., thinning), to get the total growth of biomass over the period. This could then be divided by the number of kilohectares in the category (and the number of years, if a multi-year period) to get average annual growth rates by category. This would then provide all the values needed to reconstruct the calculations in a comparable form to those from countries with minimal data.

The national emission/removal estimates presented in this form would then be easily understood and compared by all other parties involved in the international climate change discussions. The intent is to provide a calculation and reporting framework which can accommodate users with vastly different levels of data available, yet allow them to present the results on a comparable basis.

Changes in forest and other woody biomass stocks may be either a source or a sink for carbon dioxide for a given year and country or region. The simplest way to determine which, is by comparing the annual biomass growth versus annual harvest, including the decay of forest products and slash left during harvest. Decay of biomass damaged or killed during logging results in short-term release of CO_2. For the purposes of the basic calculations, the recommended default assumption is that all carbon removed in wood and other biomass from forests is oxidised in the year of removal. This is clearly not strictly accurate in the case of some forest products, but is considered a legitimate, conservative assumption for initial calculations. Box 5 provides some further discussion of this issue.

BOX 5
THE FATE OF HARVESTED WOOD

Harvested wood releases its carbon at rates dependent upon its method of processing and its end-use: waste wood is usually burned immediately or within a couple of years, paper usually decays in up to 5 years (although landfilling of paper can result in longer-term storage of the carbon and eventual release as methane or CO), and lumber decays in up to 100 or more years. Because of this latter fact, forest harvest (with other forms of forest management) could result in a net uptake of carbon if the wood that is harvested is used for long-term products such as building lumber, and the regrowth is relatively rapid. This may in fact become a response strategy.

For the initial calculations of CO_2 emissions from changes in forest and other woody biomass stocks, however, the recommended default assumption is that all carbon in biomass harvested is oxidised in the removal year. This is based on the perception that stocks of forest products in most countries are not increasing significantly on an annual basis. It is the net change in stocks of forest products which should be the best indicator of a net removal of carbon from the atmosphere, rather than the gross amount of forest products produced in a given year. New products with long lifetimes from current harvests frequently replace existing product stocks, which are in turn discarded and oxidised. The proposed method recommends that storage of carbon in forest products be included in a national inventory only in the case where a country can document that existing stocks of long term forest products are in fact increasing.

If data permit, one could add a pool to Equation 1 (1) in the changes in forest and other woody biomass stocks calculation to account for increases in the pool of forest products. This information would, of course, require careful documentation, including accounting for imports and exports of forest products during the inventory period.

The net growth of biomass stocks (and accumulation of carbon) depends on the type of biomass stock and the intensity of harvesting. Well managed commercial forests, replacing natural forests, would over the long term be expected to have net emissions close to zero. In many cases, where historically cleared areas are regrowing under commercial management, with limited logging, the forest areas are currently a net sink. If forests (or parts of forests) are logged or harvested at a rate which exceeds regrowth, then there is a net loss of carbon.[13]

Establishment of plantations and other tree planting activities result in absorption of CO_2 from the atmosphere and storage of this carbon until the vegetation is burned or decays. Restocking of managed forests, planting of urban, village and farm trees, and establishing plantations on unforested lands, therefore, result in an uptake of carbon from the atmosphere, at least until the biomass is harvested and enters a decay pool, or the system reaches maturity. The effect of plantation establishment can be to create a net sink for carbon even if the plantation is harvested for products that are rapidly oxidised (e.g., fuelwood). If the plantations are harvested so that there is no net loss of biomass over time (i.e., harvested in a sustainable fashion), then the rate of carbon accumulation on land is positive (or at least non-negative) and tied directly to changes in the area of plantations and their average biomass.

The conversion of natural forests to plantations may result in an initial loss of biomass carbon due to an initial reduction in standing biomass. If plantations are established by first clearing existing forests, the initial loss should appear under *forest and grassland conversion* below. Reaccumulation of biomass in these plantations in subsequent years would be accounted for here under *changes in forest and other woody biomass* stocks. The approach accounts for all plantations in operation in the inventory year, including both previously planted and newly established plantations.

The method for calculating the net changes in biomass stocks is shown in Equation 1. For non-forest trees such as village and farm trees, accounting would be done on the basis of numbers of trees (e.g., in thousands) rather than for hectares of land. The calculations would be the same, except that average annual growth would be expressed in tons dm per thousand trees rather than per hectare.

The recommended unit of calculation is tonnes of dry biomass, and it is necessary to convert to carbon for emissions estimation. A general default value of 0.45 tonnes-C/tonne dry biomass is recommended for all biomass calculations. If more accurate conversion values are available for the particular system, these should of course be used.

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[13] In addition, logging provides access to previously inaccessible forests, thereby facilitating degradation of forests by activities such as fuelwood collection, habitation, and agricultural activity.

EQUATION 1

(1)

hectares of land in a particular category (e.g., plantations)

x average annual growth per hectare in biomass

=

gross annual growth increment.

total biomass increment is the sum of all relevant categories.

(2)

total harvest by category (including fuelwood gathering)

x expansion ratio to treat slash

=

gross annual biomass loss.

total harvest and other biomass loss is the sum of all relevant categories of harvest.

(3)

total annual growth increment

- total annual biomass loss

=

annual biomass change (positive or negative).

Growth Increments

Estimates of average annual accumulation of dry matter as biomass per hectare are presented for forests naturally regrowing by broad category in Table 5-1. These values can be used as default values for growth rates in similar managed forest categories if no other information is available. For forests which are more intensely managed (e.g., with periodic thinning, restocking, etc.) annual growth increments could be quite different.. Values for some typical plantation species are presented in Table 5-2 and can be used as default values. As discussed in notes in these tables, average growth rates represent a great deal of variability within regions and even from site to site. It is always strongly recommended that locally available data be used or developed if possible in national inventory calculations.

TABLE 5-1
ANNUAL AVERAGE ABOVEGROUND BIOMASS UPTAKE BY NATURAL REGENERATION

tonnes dm/ha

Tropical Regions	Forest Types					
	Moist Forests		Seasonal Forests		Dry Forests	
	0-20 Years	20-100 Years	0-20 Years	20-100 Years	0-20 Years	20-100 Years
America	8.0	0.9	5.0	0.5	4.0	0.25
Africa	11	1.0	7.0	0.7	4.0	0.25
Asia	11	1.0	7.0	0.7	4.0	0.25

Note: Growth rates are derived by assuming that tropical forests regrow to 70% of undisturbed forest biomass in the first twenty years. All forests are assumed to regrow to 100% of undisturbed forest biomass in 100 years. Undisturbed forest biomass values are from Table 5-3. Assumptions on the rates of growth in different time periods are derived from Brown and Lugo, 1990.

	0-20 Years	20-100 Years
Temperate Forests		
Evergreen	3.0	3.0
Deciduous	2.0	2.0
Boreal Forests	1.0	1.0

Note: Temperate and boreal forests actually require considerably longer than 100 years to reach the biomass density of a fully mature system. Harmon et al. (1990), for example, report carefully designed simulations indicating that a 100-year old stand of douglas fir would contain only a little over half the biomass of a 450-year old growth stand of the same species. There is also evidence that growth rates in temperate and boreal systems are more nearly linear over different age periods than is the case in tropical systems. Nabuurs and Mohren (1993) suggest that growth rates for several different species in temperate and boreal zones rise slowly to peak at ages of 30-55 years and decline slowly thereafter. This suggests that using the same default values for 0-20 year and 20-100 years may be a reasonable first approximation. Nabuurs and Mohren (1990) also illustrate that growth rates may vary as much as a factor of ten for stands of the same species and age, depending on site-specific conditions. The table values are very general representative global values from Houghton et al. (1983 and 1987).

ALL OF THESE REGIONAL AVERAGE GROWTH RATES SHOULD BE CONSIDERED INDICATIVE ONLY. IF FORESTS ARE A SIGNIFICANT PART OF A COUNTRY'S TOTAL GHG INVENTORY, LOCALLY AVAILABLE DATA OR EXPERT JUDGEMENT SHOULD BE SOUGHT TO DEVELOP VALUES REFLECTING CONDITIONS AND PRACTICES.

TABLE 5-2
AVERAGE ANNUAL ACCUMULATION OF DRY MATTER AS BIOMASS IN PLANTATIONS

Forest Type	Annual Increment in Biomass (tonnes dm/hectare/year)
Tropical	
Acacia spp.	15.0
Eucalyptus spp.	14.5
Tectona grandis	8.0
Pinus spp.	11.5
Pinus caribaea	10.0
Mixed Hardwoods	6.8
Mixed Fast-Growing Hardwoods	12.5
Mixed Softwoods	14.5
Temperate	
Douglas fir	6.0
Loblolly pine	4.0

Sources: Derived from Brown et al., 1986.
Farnum et al., 1983.

Note:
These are average accumulation rates over expected plantation lifetimes; actual rates will vary depending on the age of the plantation. The data for the temperate species are based on measurements in the US. Data on other species, and from other regions, should be supplied by individual countries (as available). Additional temperate estimates by species and by country can be derived from data in ECE/FAO (1992), assuming that country averages of net annual increment for managed and unmanaged stands are reasonable approximations for plantations.

Biomass Loss

Two approaches can be used to estimate biomass harvest and other losses from managed forests. Depending on the data collection and typical forestry practices in a given country, it may be appropriate to use either approach alone, or use both if the two approaches complement each other. This judgement must be made by national experts in each country.

Commercial Harvest Statistics The first, and obvious, approach is to use statistics on amounts of biomass actually removed from forests. In countries where commercial harvests of various kinds make up a large majority of total biomass losses, and statistics are well maintained, this may be the only approach needed. Country-specific estimates of commercial harvest statistics are provided in annual FAO Forest Products Yearbooks (1993b), and periodic Assessments (e.g., FAO, 1993a), and are also generally available from national governments.

In using commercial harvest statistics, users must pay careful attention to the units involved. Commercial harvest statistics are often provided for the commercial portion of biomass only, in cubic metres (m^3) of roundwood. If this is the case, values will need to be converted to tons of dry biomass, and total biomass removed including slash. Some general default values for converting volume data to tons are 0.65 t dm/m_3 for deciduous trees and 0.45 t dm/m^3 for conifers. See Box 6 for more detailed information. To account for the biomass lost beyond the commercial wood portion, expansion ratios can be applied. Some general default values from the literature are 1.75 for undisturbed forests and 1.90 for logged forests.[14] There is considerable variability in these conversion values and expansion ratios, so it is highly desirable to use more specific locally available data. Also, some commercial harvest data may be reported as equivalent total biomass (i.e., expansion ratios already applied). It is important to check carefully the information in the original harvest data to ensure that expansion ratios are used only where appropriate.[15]

BOX 6
VARIABILITY IN DENSITIES OF TREE SPECIES

There is considerable variation in average densities for different tree species. While the broad average default values given in the text can be used for initial calculations, it is much better to use actual measured average values if available, or literature values specific to the dominant species in a particular forest. Dixon et al. (1991), for example give densities for over 150 individual species, which range from 0.31 to 0.86 g/cm^3. Other sources of wood densities include USDA Forest Service (1987), Cannell (1984), Schroeder (1992), Dewar and Cannell (1992), UN ECE/FAO (1992), Nabuurs and Mohren (1993) and Hamilton (1985).

Fuelwood Consumption Accounting In many countries, however, commercial harvest statistics will give only a partial account of wood removals and may need to be supplemented with an alternative approach. Significant amounts of biomass may be removed from forests on an informal basis (i.e., they are never accounted for in commercial statistics). This is generally true where "traditional" biomass fuels make up a major share of total fuel used in residences and small commercial enterprises.

The alternative approach, Fuelwood Consumption Accounting, first estimates fuelwood consumed based on per capita consumption data and population statistics. This accounting should also consider charcoal consumption, and "back out" an estimate of the wood which must have been consumed in traditional charcoal manufacture. The Fuelwood Consumption Accounting approach is discussed in more detail in the Energy chapter, in the section on emissions from traditional biomass fuels. Results from this type of accounting can be used in calculations of *changes in forest and other woody biomass stocks.*

Any wood which was extracted from cleared forests and used for fuel, will already have been accounted for in the *forest and grassland conversion* calculations above. This amount should be subtracted from total wood consumed directly for fuel and for traditional charcoal making, to determine the amount which must have come from remaining managed forests. The result of this calculation can then be combined with any commercial harvest amounts to produce a total amount of biomass lost from managed forests.

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[14] Volume to mass conversions and expansion factors are taken from Brown et al., 1989 which reports on tropical forests. However, the values are in the range of those reported by ECE/FAO (1992) for temperate forests.

[15] If significant amounts of non-commercial biomass (slash) are burned on site during harvest, then emissions from this burning should be treated as described for burning associated with forest or grassland conversion in the next section. A portion of the burned carbon would be stored as unburned charcoal, and non-CO_2 gases should also be calculated.

There is an implicit assumption that slash is not accumulating. The instantaneous release of CO_2 from the current year's slash that is explicit in Equation 1 (2) is a simple mathematical device to treat slash oxidation from previous years under the assumption that the slash pool is not changing. The expansion ratio for slash in Equation 1 (2) could be modified to address the destruction of belowground biomass left after harvest. Treatment of carbon released from belowground biomass (e.g., roots) is discussed in the "Refinements in Calculations" section of this chapter.

Finally, although plantation establishment usually results in an accumulation of soil carbon, conversion of natural forests to plantations could cause a net loss of carbon from the soil (Holt and Spain, 1986). Because of the uncertainty about the magnitude and direction of the soil carbon change in plantation systems, this is ignored in the basic calculations. This issue is discussed in the Refinements section.

The amount of biomass removed from forests and other woody biomass stocks in the inventory year should be subtracted from the annual growth in these stocks for the same year to arrive at the annual change in biomass stocks, positive or negative [Equation 1 (3)]. This result should be converted to a change in C (using the general default value of 0.45 t C/t dm, if necessary), and to CO_2 (using the ratio 44/12). A positive value for CO_2 in stocks is a CO_2 removal from the atmosphere while a negative value is an emission. For reporting purposes, the sign should be changed to conform to the convention that emissions are positive and removals are negative (i.e., negative emissions).

5.2.3 Forest and Grassland Conversion

CO_2 release

This category includes conversion of existing forests and natural grasslands to other land uses, such as agriculture. The calculation of carbon fluxes due to forest and grassland conversion is in many ways the most complex of the emissions inventory components. Because of the long-term responses of biological systems, it is necessary to consider forest clearing activity over three different time-scales and to sum the results to estimate the total flux in the current year. Also, as with all categories of forest management and land use change activity, it is necessary to determine *net* CO_2 flux.

Forests can be cleared to convert land to a wide variety of other uses, including agriculture, highways, urban development, etc.[16] In all cases there is a net carbon release to the atmosphere which should be accounted for in this calculation. The predominant current cause of forest clearing is conversion to pasture and cropland in the tropics. This is accomplished by an initial cutting of undergrowth and felling of trees. The biomass may then be combusted in a series of on-site burns or taken off site to be burned as fuel, or perhaps used for forest products. A portion of the biomass remaining on site as slash is not actually combusted and remains on the ground where it decays slowly.[17] Some of the decay of remaining carbon left on the ground is probably accomplished by termites, which produce both CO_2 and CH_4.[18] However, the methane release from cleared, unburned biomass is very difficult to quantify and is ignored for purposes of the basic calculation, where all of the carbon in biomass which decays is assumed to be released as CO_2. Of the portion burned on site, a small fraction of the carbon remains as charcoal, which resists decay for well over 100 years or more. There is a great deal of uncertainty about the fraction of carbon which remains unburned in charcoal under these conditions and also about the ultimate fate of this charcoal.[19] The remainder is released instantaneously to the atmosphere. For biomass removed for fuelwood, the fate is very similar. A small fraction of the carbon remains in unburned charcoal which effectively provides long term storage, while the majority of the carbon is released to the atmosphere.

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[16] Conversion of tropical forests to pasture and cropland accounts for the largest share of global forest clearing and resulting CO_2 emissions. The discussion and default information focus on this case, as it is most important that national inventories account for the largest contributions to emissions first. Forest clearing for other purposes (e.g., urban development) should also be accounted for to the extent possible. As less default information is provided for these cases, this will require national experts to provide input data.

For conversion of grasslands to crop or pasture lands, the default assumption is that there is no change in aboveground biomass between the pre-conversion natural grassland and the post-conversion crops or pasture. This assumption can be varied if there are locally available data that show a net change. See Box 7.

Forest and grassland conversion also results in CO_2 emissions through soil disturbance, particularly when the conversion is to cultivated or tilled lands. When forests are converted to croplands, a fraction[20] of the soil carbon may be released as CO_2, primarily through oxidation of organic matter. This can be a long term process which continues for many years after the change in land use occurs. The basic calculations allow for estimation of loss in soil carbon due to land conversions. However, because of the uncertainty in current understanding of this component, and the difficult historical data requirements, the users are encouraged to exercise their own judgement as to whether or not to include this calculation in the basic estimates.

Calculations

Emissions of CO_2 due to forest and grassland conversions are calculated through a sequence of easy steps treating:

- the net change in aboveground biomass carbon

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[17] For instance, see Houghton (1991); Crutzen and Andreae (1990). The decay rates generally depend on several factors including humidity, temperature, and litter quality.

[18] This issue is discussed in the section on possible refinements to the methodology.

[19] The portion of burned carbon that remains on the ground as charcoal is highly uncertain. Measurements following burning of a forest for conversion to pasture indicate that 2.6 per cent of the pre-burn aboveground carbon, or 8.5 per cent of the burned carbon, is converted to charcoal (Fearnside et al., 1990a). According to Fearnside (1990b), pastures are typically burned two to three times over about a 10-year period. Under such a scenario, the latter burns probably result in combustion of some of the charcoal formed during the first burn and formation of additional charcoal. Fearnside (1990b) estimates that about 4.6 per cent of the pre-burn aboveground carbon, or 10.1 per cent of the burned carbon, is converted to charcoal under this scenario. Based on results of observations in the Brazilian Amazon (Fearnside, 1990a) and in a Florida pine forest (Comery, 1981), Crutzen and Andreae (1990) adopt charcoal values of 5 per cent of the pre-burn aboveground carbon and 10 per cent of the burned carbon for clearing in the tropics.

[20] On average about 25-50 per cent of the soil carbon, as discussed in Houghton et al. (1983).

- the portion of this change that is burned in the first year versus the amount left to decay over a longer time period
- for the burned portion, loss to the atmosphere versus long term storage in charcoal
- current emissions from decay of biomass cleared over the previous decade
- if estimated, current releases of carbon from soils due to conversions over the previous 25 years

Net change in aboveground biomass

First, the amount of aboveground biomass affected by conversion in the emissions inventory year[21] is calculated by multiplying the annual forest area (or savannas, grasslands, etc., if appropriate) converted to pasture or cropland or other land uses by the net change in aboveground biomass. This calculation is carried out for each relevant forest/grassland type and, if appropriate, by region within a country.[22] The *net change* is the difference between the density (t dm/ha) of aboveground biomass on that forest/grassland prior to conversion, and the density of aboveground living biomass (t dm/ha) remaining as living vegetation, after clearing. The after clearing value includes the biomass that regrows on the land in the year after conversion and any original biomass which was not completely cleared.

Tables 5-3 and 5-4 provide a range of values for aboveground biomass in forests prior to clearing, which can be used as default data if more appropriate and accurate data are not available in a given country.[23] For aboveground biomass after clearing, it is necessary to account for any vegetation (i.e., crops or pasture) that replaces the vegetation that was cleared. A reasonable figure for crops or pasture is 10 tonnes of dry biomass per hectare (Houghton et al. 1987). The recommended default assumption is that all of the original aboveground biomass is destroyed during clearing. If locally available data indicate that some fraction of the original biomass is left living after clearing, this should be added to the after clearing value.

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[21] For simplicity of explanation, the discussion refers to the inventory year as though data for a single year were the desired input. However, as noted in the overview, for land use and forestry emissions estimates, it is recommended that data averaged over three years be used in place of annual data.

[22] Defining regions will require balancing data availability, biological and land-use heterogeneity, and practical considerations such as the available time and effort. Furthermore, developing adequate land-use and land-use change data is a central issue. In the case of land-clearing, these data would likely be obtained from a combination of departments of land management, agriculture, and forestry. These data will come at a variety of scales in time and space, and producing consistent records will be a challenging task to all countries. In time, new internationally-based remote sensing programs could greatly facilitate this task; this is discussed in the technical appendix.

[23] As in the case of land-use data, developing appropriate biomass data is a challenging task. In theory, it can be obtained directly by destructive sampling but this is unrealistic for adequate coverage for even small countries. An alternative approach is to use inventory or production data where one exploits volumetric data on marketable timber and uses a sequence of expansion factors to convert this to total stemwood, total above ground biomass volume, and total biomass volume. See the references to Tables 5-3 and 5-4.

Box 7

ABOVEGROUND BIOMASS IN GRASSLANDS

Conversion of a grassland to cultivated land may result in net CO_2 emissions to the atmosphere due to soil disturbance and resultant oxidation of soil carbon. In the simple default calculations, it is assumed that there is no net reduction in standing biomass because aboveground biomass densities of grasslands are approximately the same as that of croplands and pasture. Therefore any changes in this aboveground pool due to the land use change are likely to generally be small in comparison to other changes in carbon stocks in terrestrial systems. Consequently, changes in aboveground biomass are ignored in the basic calculation. As with all default assumptions, users are encouraged to vary this one if they believe it is inaccurate for their conditions. Some grasslands can contain significantly more standing biomass than the default estimate of 10 tonnes dry matter/hectare for grasslands. If national experts have data locally available and differences are significant, these values should be used. In this case the assumption of no net change in aboveground biomass would not be valid. The net change in aboveground biomass in this situation would be determined with exactly the same procedure as used in the forest clearing case.

TABLE 5-3
DRY MATTER IN ABOVEGROUND BIOMASS IN TROPICAL FORESTS

(tonnes dm/hectare)

	Moist Forests		Seasonal Forests		Dry Forests (or Woody Savannas	
	Primary	Secondary	Primary	Secondary	Primary	Degraded
America	230	190	140	120	60	25
Africa	300	240	190	150	36	16
Asia	300	150	190	95	60	20

Sources: These average regional values are presented for illustrative and comparison purposes. They are volume-based estimates derived from a variety of sources. Recent revised estimates for aboveground biomass in undisturbed moist forests were taken from Brown and Lugo (1992) for Tropical America, Brown et al. (in press) for Asia and Brown (1993) for Africa. Corresponding values for secondary forests were derived on the basis of the ratios of these biomass densities to the biomass density for undisturbed forests as reported in Brown et al. (1989). For seasonal forests, the ratios of the densities for tropical moist and seasonal forests for Asia, reported in Houghton and Hackler (1994), was applied to the regional values for moist forests, to obtain regional estimates for seasonal forests. Values for dry forests are "open forest" values from Brown and Lugo (1984) and multiplied by 0.77 to obtain the aboveground portion only.

Note: Broad regional estimates of biomass densities are highly uncertain. Estimates based on destructive sampling involve direct measurements (weighing) of biomass harvested from an experimental site. Volume-based estimates are generally somewhat lower than those based on destructive sampling and are derived from FAO data on commercial wood volumes that are converted to mass units based on average wood densities and ratios of aboveground biomass to commercial biomass (i.e., expansion factors). Researchers agree that there is a great deal of variability from stand to stand and among subregions within large regions. For example, Brown and Lugo (1992) report biomass estimates ranging from 166 to 332 t dm/ha for individual stands in moist Amazonian forests.

There are also some differences in the way different experts interpret the available data to produce averages. Fearnside (1993) has documented similar ranges of variability from stand-to-stand and produced somewhat higher average estimates of aboveground biomass for the Brazilian Amazon than those of Brown and Lugo (1992). His estimates are:

	Average for Brazilian Amazon (t dm/ha)	Forests Actually Cleared in 1990 in Brazilian Amazon (t dm/ha)
Undisturbed forests	308	291
Secondary forests		271

Fearnside (1992) and Brown and Lugo (1992) discuss in detail a number of possible explanations for the differences in results.

REGIONAL DEFAULT ESTIMATES FOR BIOMASS DENSITY MAY BE USED AS AN INITIAL STARTING POINT OR FOR COMPARISON PURPOSES. HOWEVER, IN ANY COUNTRY FOR WHICH FOREST CONVERSION OR REGROWTH IS A SIGNIFICANT SOURCE OR SINK, LOCAL EXPERTS AND MEASUREMENTS SHOULD BE CONSULTED TO DEVELOP MORE ACCURATE VALUES REFLECTING LOCAL CONDITIONS.

TABLE 5-4
DRY MATTER IN ABOVEGROUND BIOMASS IN TEMPERATE AND BOREAL FORESTS
(tonnes dm/hectare)

	Temperate Forests		Boreal Forests
	Evergreen	Deciduous	
Primary	295	250	165
Secondary	220	175	120

Source
Primary forest estimates from Whittaker and Likens (1973); secondary forest estimates from Houghton et al. (1983). Total biomass estimates were converted to aboveground biomass by multiplying by 0.83 (Leith and Whittaker, 1975). Alternative estimates of aboveground biomass per hectare, by country, for coniferous species and non-coniferous species, can be derived using statistics provided in ECE/FAO (1992). Data are provided for 37 countries.

Immediate emissions from burning

The biomass that is cleared has one of three immediate fates:

1. a portion may be burned on site;
2. a portion may be removed from the conversion site and used as fuelwood, or for products;
3. a portion is converted to slash and decays on site to carbon dioxide over a decade or so. Some estimates in the literature suggest that a global average of about 50 per cent of the cleared biomass is burned in the first year with the remaining 50 per cent left to decay (e.g., Houghton, 1991; and Crutzen and Andreae, 1990). This value could be used as a default for first order calculations if the user does not have access to more appropriate local information. It is important to recognise that this average is dominated by practices in Latin America which has the largest current rates of deforestation. There are certainly wide variations in burning practices between and within regions. It is **highly recommended** that, for final inventories, users provide their own values reflecting practices and burning conditions in the regions of interest, rather than using the global default value. To calculate the gross amount of carbon released in the current year to the atmosphere it is necessary to consider the burned portions and the decaying portion over different time horizons.

To estimate the CO_2 released by the burning of cleared aboveground vegetation, estimate a) the fraction of the affected biomass that is subjected to burning (on and off site - the remaining, disturbed biomass is slash) and b) the fraction of the burned biomass that is oxidised. The fraction of burned biomass which does not oxidise remains as charcoal. The amount of biomass oxidised is converted to carbon units to estimate the carbon flux from burning.[24] A reasonable average for converting from dry biomass to carbon content is to multiply dry biomass by 0.45.[25] Of the portion of cleared biomass which is burned, some of this may be burned in the field to facilitate clearing, and some may be removed and used as fuel. The portion which is burned in the field is used subsequently for calculating the non-CO_2 trace gas emissions from open burning of cleared biomass, in the next section. The amount removed for fuel is important for calculations of fuel wood extracted from *forest and other woody biomass stocks* as described earlier in these basic calculations.

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[24] As discussed elsewhere in these *Guidelines* this method counts the carbon actually emitted as CO and CH_4 as though it were carbon dioxide. Later in this chapter, these emissions of CO and CH_4 will also be estimated separately.

[25] The range most cited is 0.43 - 0.58; hence some suggest that 0.5 is a more appropriate default assumption.

Emissions from decay

The aboveground biomass which remained on site but was not burned will oxidise in roughly a decade, and this historical release associated with land clearing must be considered. The 10 year period is a recommended default value, as a reasonable historical horizon in light of the twin realities of data availability and biological dynamics (see Houghton, 1991; and Crutzen and Andreae, 1990). This can be varied if the user has data or a strong rationale to suggest that a longer or shorter average decay time is more representative of local conditions. The "committed" flux calculation simply accounts for the current oxidising of material left unburned during the specified historical decay period.

The decay phenomenon can be simply characterised for emissions estimation purposes. Each year, some portion of the cleared aboveground biomass is left as slash, and we assume that 10 per cent of this decomposes each year. Therefore, the total carbon being released to the atmosphere in the inventory year is a function of the land clearing rate for each of the past 10 years, and the portion of the aboveground carbon remaining on site but not combusted each year. The current year emissions from decay of biomass cleared in a historical year would be 10 per cent of the total decay. The total current emissions from decay of historically cleared biomass would then be the sum of the current estimated emissions from biomass cleared in each of the ten historical years.

In order to simplify the calculations, the methodology uses decadal average values for the land clearing and portion left to decay. Working with average values, one would divide the total emissions from decay by 10 to get the contribution of one "average" historical year's clearing to current emissions, then multiply by 10 to account for ten historical years' clearing which could be expected to affect current emissions. Obviously the division by 10 and multiplication by 10 cancel each other and can be ignored. Therefore, the flux in the inventory year from aboveground vegetation decay due to current and historical land clearing is simply expressed in Equation 2.

EQUATION 2

average annual land clearing over the period

x the average quantity of aboveground dry biomass per hectare remaining on site as slash but not burned (either oxidised or converted to charcoal)

x carbon content of dry biomass

=

flux in the inventory year from historical land clearing of the aboveground vegetation

Soil carbon release

For calculating the annual CO_2 flux associated with the loss of soil carbon following forest clearing or grassland conversion, the methodology is essentially the same as the approach for treating the historical flux from slash. The time horizon suggested is twenty-five years. The historical release from soils is simply the average annual land clearing times the change in carbon stock in soil between the original land use and a twenty-five year old pasture or crop land. For simplicity, it is assumed that the soil carbon release is linear over the 25 year period.[26]

The annual rate of soil carbon loss would be total change in soil carbon from before conversion levels to the final level divided by 25. The currently available information on soil carbon changes after conversions relates primarily to temperate and boreal forests and temperate grasslands. In these cases there is evidence that perhaps 50 per cent of the soil carbon in the active layer (roughly the top one meter) is lost over roughly a 50 year period, with most of this loss occurring in the first 25 years.[27]

These values are highly uncertain. The actual rate of soil carbon loss in a particular area of agricultural land, is a function of the specific agricultural use and management practices as discussed in the refinements section of this chapter. There is evidence that, in some cases, the conversion of forests and grasslands to cultivated lands has actually increased carbon stocks in certain systems. However, the general values above could be used as a default for initial calculations, if more accurate information or measurements are not available to users. This would imply that the annual rate of soil carbon loss would be 2 per cent (50 per cent/25 years).

The contemporary flux associated with past land use change could be calculated by multiplying the number of hectares of land converted in each of the previous 25 years by the annual per hectare loss in soil carbon and summing. Alternatively, the *average* annual historical conversion rate over a twenty-five year period could be multiplied by the annual loss rate times twenty-five. The average rate of conversion is simply the total hectares converted over the period divided by 25 years.

It is an open question if the conversion of tropical forests and grasslands to agriculture, especially pasture, results in loss of soil carbon as CO_2.[28] Data on changes in soil carbon in tropical systems are sparse. Therefore, no default assumptions can be provided for this region. Pending resolution of the scientific debate on this issue, it is left to the judgement of users whether or not to include this component in the calculations, and what values to use for the portion of carbon lost. Tables 5-5 and 5-6 provide average values for soil carbon in tropical, temperate, and boreal forest systems. Very crude general default values for grasslands are 60 tonnes/ha for tropical systems and 70 for temperate systems.[29]

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[26] In temperate systems, in fact, most of the soil carbon is released in the first 5 years after clearing; the rest is released over the next 20 years. See Houghton (1991).

[27] See Houghton et al., 1983.

[28] The issue of soil carbon change following land-clearing in the tropics is an important research topic. There is evidence that there is a rapid soil carbon loss followed by soil carbon accumulation depending upon the type of grasses that are used in pasture (e.g., Fearnside, 1980, 1986; Buschbacher, 1984; Cerri et al., 1988; and Lugo et al., 1986). Clear cutting of tropical forests does not appear to release soil carbon (Keller et al., 1986). The current status of the science, however, may not provide an adequate basis for recommending values for inclusion of this aspect of the carbon cycle in emission calculations at this time. Further research needs to be done.

[29] Post, et al., 1982.

In the initial application of basic calculations, soil carbon losses from forest and grassland conversion can be ignored for tropical countries unless the user has access to data on the rate of soil carbon loss (or accumulation) after this land use change. This is an important research issue, as discussed in the refinements section of this chapter. As a result, in the initial application of the basic calculations to the land use change of converting grasslands to cultivated lands, default values are recommended only for changes in the soil carbon pool in temperate grassland systems. The simple calculation structure would be the same for tropical systems but the use of available default assumptions and values (based on temperate systems) is not recommended.

TABLE 5-5
CARBON IN SOILS IN TROPICAL FORESTS

(tonnes carbon/hectare)

	Moist	Seasonal	Dry
America	115	100	60
Africa	115	100	60
Asia	115	100	60

Source:
Post, W.M., et al., 1982.

Note:
The forest categories presented here are different from those presented in Tables 5-2 and 5-3. The average of the values for moist and seasonal forests presented above can be used for both closed forest types (broadleaved and coniferous); the values for dry forests presented above can be used for open forests.

TABLE 5-6
CARBON IN SOILS IN TEMPERATE AND BOREAL FORESTS

(tonnes carbon/hectare)

	Temperate Forests		Boreal Forests
	Evergreen	Deciduous	
Primary	134	134	206
Secondary	120	120	185

Source: Schlesinger, 1977, as cited in Houghton et al., 1983; and Houghton et al., 1987.

Note: Alternate values for soil carbon in tropical, temperate, and boreal forests, by continent, are available in Zinke et al. (1984). However, care must be taken when choosing appropriate soil carbon values in Zinke et al. (1984). Ecosystem types in this reference may not match the ecosystem types for which clearing data and biomass estimates are available.

As with emissions from decay of aboveground biomass, the recommendation is to use average values for the rate of land conversion, soil carbon content and portion of soil carbon lost over time. Again, for the same reason, the theoretical requirement to multiply and divide by 25 cancel. The calculation of current emissions (from soils in forest cleared over 25 years) is expressed in Equation 3.

EQUATION 3

the average annual conversion rate over the last 25 years

x change in soil carbon between a forest or grassland system and a 25 year old pasture or crop land

=

current emissions (from soils in land converted over 25 years)

The estimate of the total carbon released in the inventory year from current and historical forest and grassland conversion is calculated by summing the current year release of carbon due to burning, either on site or as fuelwood, the average long-term annual release of carbon from decay of biomass cleared over the base decade, and, if estimated, the current year release of soil carbon due to land clearing over the previous 25 years.

Burning of Forests: Non-CO_2 Trace gases

Where there is open burning associated with forest clearing (or other land use change), it is important to estimate the emissions of methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and oxides of nitrogen (NO_x, i.e., NO and NO_2). The approach is essentially the same as that used for non-CO_2 trace gases for all burning of unprocessed biomass, including traditional biomass fuels, savanna burning and field burning of crop residues. For all these activities there is a common approach in the proposed methodology in that crude estimates of trace gas emissions can be based on ratios to the total carbon released by burning. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. To handle nitrogen trace gases, ratios of nitrogen to carbon in biomass are used to derive total nitrogen released from burning, and then emissions of N_2O and NO_x are based on ratios to total nitrogen release. Table 5-7 provides suggested default values for trace gas emission ratios.[30] These are presented with ranges which emphasise their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[31]

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[30] The emission ratios used in this section are derived from Crutzen and Andreae (1990), Delmas (1993) and Lacaux (1993). They are based on measurements in a wide variety of fires, including forest and savanna fires in the tropics and laboratory fires using grasses and agricultural wastes as fuel. Research will need to be conducted in the future to determine if more specific emission ratios, e.g., specific to forest fires, can be obtained. Also, emission ratios vary significantly between the flaming and smouldering phases of a fire. CO_2, N_2O, and NO_x are mainly emitted in the flaming stage, while CH_4 and CO are mainly emitted during the smouldering stage (Lobert et al., 1990). The relative importance of these two stages will vary between fires in different ecosystems and under different climatic conditions, and so the emission ratios will vary. As inventory methodologies are refined, emission ratios should be chosen to represent as closely as possible the ecosystem type being burned, as well as the characteristics of the fire.

[31] Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible, or to provide some expression of the level of confidence associated with various point estimates provided in the inventory. Procedures for reporting this uncertainty or confidence information are discussed in *Volume I: Reporting Instructions*.

TABLE 5-7

EMISSION RATIOS FOR OPEN BURNING OF CLEARED FORESTS

Compound	Ratios	
CH_4	0.012	(0.009 - 0.015) [1]
CO	0.06	(0.04 - 0.08) [2]
N_2O	0.007	(0.005 - 0.009) [3]
NO_x	0.121	(0.094 - 0.148) [3]

Sources: [1] Delmas, 1993
[2] Lacaux, 1993
[3] Crutzen and Andreae, 1990

Note:
Ratios for carbon compounds, i.e., CH_4 and CO, are mass of carbon compound released (in units of C) relative to mass of total carbon released from burning. Those for the nitrogen compounds are expressed as the ratios of emission (in units of N) relative to total nitrogen released from the fuel.

All of the crude biomass burning calculations have two steps: 1) estimating total carbon released, and 2) applying emission ratios to estimate emissions of the non-CO_2 trace gases. In the case of burning of cleared forests (and other land conversion if appropriate), step 1 has been carried out in the previous section which included the estimation of carbon emissions from the portion of biomass from conversions which is burned on site in the inventory year. The total carbon release from this on site burning (not including any carbon released from decay or soils) provides the basis for the inventory year release of non-CO_2 trace gases. To complete the calculations, it is necessary only to add step 2 of the calculation – the release of non-CO_2 trace gases from current burning.

Once the total carbon released from on site burning of cleared biomass has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated (Crutzen and Andreae, 1990). The total carbon released due to burning is multiplied by the emission ratios of CH_4 and CO relative to emissions of total carbon to yield total emissions of CH_4 and CO (each expressed in units of C). The emissions of CH_4 and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights.

To calculate emissions of N_2O and NO_x, first the total carbon released is multiplied by the estimated N/C ratio of the fuel by weight (0.01 is a general default value for this category of fuel (Crutzen and Andreae, 1990)) to yield the total amount of nitrogen (N) released. The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the total N released from the fuel to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28 and 46/14, respectively.[32]

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[32] The molecular weight ratios given above for the emitted gases are with respect to the weight of nitrogen in the molecule. Thus for N_2O the ratio is 44/28 and for NO_x it is 46/14. NO_2 has been used as the reference molecule for NO_x.

The trace gas emissions from burning calculation are summarised as follows:

- CH_4 Emissions = (carbon released) x (emission ratio) x 16/12
- CO Emissions = (carbon released) x (emission ratio) x 28/12
- N_2O Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 44/28
- NO_x Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 46/14

5.2.4 Abandonment of Managed Lands

If managed lands, e.g., croplands and pastures, are abandoned, carbon may re-accumulate on the land and in the soil. The response of these converted systems to abandonment depends upon a complex suite of issues including soil type, length of time in pasture or cultivation, and the type of original ecosystem. It may be that some of the abandoned agricultural lands are too infertile, saline, or eroded for regrowth to occur. In this case, either the land remains in its current state or it may further degrade and lose additional organic material (i.e., carbon in the biomass and the soils). Therefore, to calculate changes in carbon flux from this activity, the area abandoned should first be split into parts: lands that re-accumulate carbon naturally, and those that do not or perhaps even continue to degrade.

In the basic calculation, only those that begin to return to an approximation of their previous natural state are considered. Those that remain constant with respect to carbon flux can be ignored. Likewise, the CO_2 flux to the atmosphere for those lands that continue to degrade is likely to be small on a global basis and hence is ignored in the initial application of basic calculations. In some countries, abandoned lands which degrade may be a significant problem and could be an important source of CO_2 emissions. Where lands continue to degrade, both aboveground biomass and soil carbon may decline rapidly, e.g., due to erosion. For countries which have significant areas of such lands this issue should be considered in a more refined calculation.

Abandoned lands must be evaluated in the context of the various natural ecosystems originally occupying them. In addition, the effect of previous patterns of abandonment should be considered while recognising the desire for simplicity and practicality. The process of recovery of aboveground biomass generally is slower than the human-induced oxidation of biomass. With this in mind and in consideration of possible data sources it is recommended that abandoned lands be evaluated in two time horizons. A twenty year historical time horizon is suggested to capture the more rapid growth expected after abandonment. A second time period – from 20 years after abandonment up to roughly 100 years – may be considered if data are available.[33]

The calculation, by original ecosystem (e.g., moist forest, dry forest, grassland) is straightforward.

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[33] It is clear that some forest systems may take longer than 100 years to return to the level of biomass contained in an undisturbed system. If data are available, it is possible to calculate carbon sinks from regrowth on lands abandoned more than 100 years prior to the inventory year. As a practical matter, however, it is unlikely that such data will be available in most countries, or that the magnitude of annual carbon accumulation would be large. Therefore, it is not generally recommended to carry these calculations back more than the specified period of 100 years.

The total area abandoned (total over the previous 20 years including the inventory year) is multiplied by

1 the average annual uptake of carbon in the aboveground biomass, and

2 the average annual uptake of carbon in the soils.

Results of these two calculations are summed to yield the current uptake of carbon due to abandonment over the previous 20 years of managed lands that are naturally regenerating to forests or grasslands.

If land use data are available to support calculations over a longer time horizon, national experts may want to consider adding a pool of forests and grasslands that are regrowing from abandonment that occurred more than 20 years ago. The growth rates of aboveground biomass in these forests would be slower than that of forests regrowing from abandonment that occurred less than 20 years ago. The same calculations can be repeated for lands abandoned more for than 20 years and up to about 100 years prior to the inventory year.

Table 5-1 presents estimates of average annual aboveground biomass accumulation in vegetation in various regrowing forest ecosystems following abandonment of cultivated land or pasture[34]. These general growth rates, averaged over large regions and many specific ecosystem types, should be considered crude approximations as applied to the particular lands regrowing in a given region or country. If more accurate data on these growth rates are locally available, they should be used. Accumulation of aboveground dry biomass can be converted to carbon using a general default conversion value for biomass – 0.45 t C/t dm.

If lands are regenerating to grassland, then the default assumption is that no significant changes in aboveground biomass occur. This can be varied based on locally available data. Default rates of soil carbon uptake for both forests and grasslands can be derived from the expected soil carbon values for fully restored natural systems and some simple assumptions. In temperate and boreal systems it can be assumed that soil carbon accumulates linearly from some base value (e.g., 50-75 per cent of original stocks). Table 5-6 provides default soil carbon values for temperate systems. Values for tropical systems are provided in Table 5-5, and crude defaults for grasslands were provided in the previous section (60 t-C/ha tropical, 70 t-C/ha temperate). Soil carbon changes in tropical systems are poorly understood and can be included or ignored in basic calculations at the discretion of national experts. To the degree possible, soil carbon in tropical systems should be treated consistently in the calculations for 1) forest and grassland conversions, and 2) abandonment of managed lands. If soil carbon losses are calculated for conversions, then soil carbon sinks should be calculated for abandonment of managed lands.

The base value at the start of the reaccumulation process in soils would depend on the average amount of time that cleared lands had been used for agricultural purposes (and the management practices utilised during the agricultural period) before abandonment. Based on the simple default assumptions for soil carbon losses from forest clearing, one could calculate the level to which soil carbon would have fallen during the agricultural use period. The default assumption is that after 25 years, soil carbon would have fallen to 50 per cent of the pre-clearing value (i.e., 2 per cent per year linear average change). For example, if the agricultural use period was 10 years before abandonment, it could be assumed that the base value in soils would be 80 per cent of original values. Available evidence is that, on average, soil carbon reaccumulates in soils after abandonment, at a slower rate than it is lost under cultivation. In the forest clearing calculations the default assumption is that soil carbon is lost at an average rate of 2 percent of the original carbon content per year. If no detailed information is available, a default assumption could be that the soil accumulation occurs linearly[35] at roughly one-half this rate after abandonment. This procedure was used to derive the values presented in the *Workbook*. The values given are 1.3 tonnes C/year for temperate evergreen and deciduous forest soils and 2.0 tonnes C/year for boreal forests. These are one percent of the values from Table 5-6 for soil carbon in primary forests. This is an important area for further research.

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[34] Values given in Table 5-1 assume linear regrowth of aboveground biomass in each of the two time periods (0-20 years and 21-100 years). In reality, as shown in Brown and Lugo (1990), the regrowth is closer to an exponential function. The calculation could be improved by breaking the 20 year period into finer segments, assuming availability of data, to determine a weighted average.

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[35] The re-accumulation of carbon in soils is not linear. Generally accumulation occurs quickly in initial stages of regrowth and slows as regrowth slows.

5.3 Refinements In Calculations

5.3.1 Introduction

There are a number of areas in which the basic calculations could be improved at least theoretically. Simplifying assumptions have been made in many places in order to produce methods consistent with data likely to be available in many countries. The basic calculations focus only on the most important categories for emissions of CO_2 within a much larger set of land use and forest management activities having some impact on GHG emission fluxes. Some activities are known to result in GHG fluxes, but cannot be quantified based on the available scientific research results. Many of these issues are summarised below to assist users in considering which, if any, of these possible refinements could be included in national inventories, either currently, or in the future as scientific understanding improves.

The first section deals with the subcategories already discussed in the basic calculations, but highlights a number of ways in which these calculations could be augmented. The second section discusses additional categories of land use change or forest management which could be added to the categories in the basic calculations.

5.3.2 Possible Refinements or Additions to Basic Categories

Changes in Forest and Other Woody Biomass Stocks

Prescribed Burning of Forests: Non-CO_2 Trace Gases

The issue of prescribed forest burning is complex because of two issues. First, there is the question of the rate of change that humans have induced and second, there is the question of releases of trace gas several years after the burning. Prescribed burning is a method of forest management by which forests are intentionally set on fire in order to reduce the accumulation of combustible plant debris and thereby prevent forest fires, which could possibly be even more destructive. This activity is primarily limited to North America and Australia (Seiler and Crutzen, 1980). Because carbon is allowed to re-accumulate on the land after burning no net CO_2 emissions occur over time, although emissions of CH_4, CO, N_2O, and NO_x result from the biomass combustion.

Some of the issues associated with prescribed forest burning, particularly in the temperate world, remain important research topics. Some have suggested that prescribed forest burning may be increasing carbon stocks in forests and hence serving as a CO_2 sink, but at the same time adding other radiatively important non-CO_2 trace gases to the atmosphere. An important issue is the change in burning rate because of human activity. Is prescribed burning, and its consequent emissions, just a man-made replacement for what would have occurred naturally? What is the rate change? If we assume that this question, the rate of change, can be answered, then the issue of trace gas release for prescribed burning is similar to trace gas emissions following forest clearing.

The second complicating issue which should be considered is the release of non-CO_2 trace gases in years after burning. This is also discussed under *forest and grassland conversion* below. The same uncertainties apply here, although this may be a less important area for prescribed burning, because the forests will be regrowing quickly, and possibly overcoming the conditions which could cause longer term trace gas emissions.

Soil carbon

In the basic calculations, no soil carbon accumulation is assumed while plantations are being established (or other tree planting activities are occurring) on previously non-forest lands. If plantations are established where natural or managed forests previously existed, then the carbon content of soils may not change significantly. However, it is possible that the establishment of plantations on previously non-forest lands could result in accumulation of soil carbon over time. Further investigation may be useful to determine whether this is a significant enough effect to warrant addition to the calculations. In addition, it is likely that different forest management practices can cause increases or decreases in soil carbon over long periods of time, as is the case in agriculture. This is an area which should be considered in future work on inventory methods.

Forest and Grassland Conversion

Forest clearing is a very complex and diverse set of activities which can have many interactions with biospheric fluxes of greenhouse gases over long periods of time. The components of this set of interactions which are included in the previous section are those on which there is general agreement among experts of their importance and simple estimation procedures. A number of other possible elements have been discussed in the scientific literature, but are controversial or difficult to calculate at present.

- **Emissions from Burning of Forests**

  A number of aspects of emissions due to burning could be treated in more detail.

  a *Subsequent burns in years after clearing.* In some cases, where forests are cleared for agricultural purposes, the land may be partially burned in the year of clearing, but may also be burned again in later years. Fearnside (1990b) indicates that pastures in the Brazilian Amazon are typically burned two or three times over about a ten year period. This would cause a larger fraction of carbon in cleared biomass to be released to the atmosphere sooner than the approach now included in the basic calculations, and would certainly increase emissions of non-CO_2 trace gases from biomass burning.

  b *Non-CO_2 trace gases released after burning.* Basic calculations address the main issues in trace gas production by burning, however, they do not treat all issues. For instance, the effect of past burning, particularly of forests, on trace gas exchanges must eventually be considered. Specifically, the instantaneous release of non-CO_2 trace gases when forests are burned is included in Land Clearing calculations. However, the longer-term release or uptake of these gases following forest burning is an important research issue and should eventually be included in refinements of calculations. The issue of the contemporary release of non-CO_2 trace gases associated with past burning is complex. For example, clearing by burning may stimulate soil nutrient loss. Measurements in temperate ecosystems (e.g., Anderson et al., 1988; and Levine et al., 1988) indicate that surface biomass burning enhances emissions of N_2O and NO_x from the soils for up to 6 months following the burn; however, in other studies measurements of N_2O emissions at a cleared and burned tropical forest site in Brazil, begun five months after the burn and continuing for a year, were not significantly different, from those taken from a nearby intact forest site (Luizão et al., 1989). The "historical" issue is obviously complex and further research is needed before an adequate methodology for emissions calculations can be proposed.

- **Delayed release of non-CO_2 trace gases after land disturbance.**

  Even when no burning is involved there may still be a release of trace gases. An experiment in a temperate forest in the northeast United States found that clearcutting resulted in enhanced N_2O flux to the atmosphere via dissolution of N_2O in the soil water, transport to surface waters, and degassing from solution (Bowder and Bormann, 1986). An experiment in Brazil found that N_2O emissions from newly clearcut tropical forests were about three times greater than those from adjacent undisturbed forests (Keller et al., 1986). Conversion of tropical forests to pasture also has been found to result in elevated N_2O emissions relative to the intact forest soils (Luizão et al., 1989; and Matson et al., 1990). Another example involves the loss of a sink for methane which, in effect, adds to the atmospheric burden of CH_4. Specifically, the loss of forest area (tropical or temperate) may also result in increased net CH_4 emissions to the atmosphere. Soils are a natural sink of CH_4 (i.e., soils absorb atmospheric CH_4), and various experiments indicate that conversion of forests to agricultural lands diminishes this absorptive capacity of soils (Keller et al., 1990; and Scharffe et al., 1990).

  Conversion of natural grasslands to managed grasslands and to cultivated lands may affect not only the net emission of CO_2 but CH_4, N_2O, and CO emissions as well. For instance, the conversion of natural grasslands to cultivated lands has been found in the semi-arid temperate zone to also decrease CH_4 uptake by the soils (Mosier et al., 1991). It is not clear what the effect on N_2O would be, unless of course nitrogen fertilisation occurs. The effect of conversion of natural grasslands to managed grasslands on trace gas emissions has not been evaluated in the field, except for the effect of associated nitrogen fertilisation on N_2O emissions. Nitrogen fertilisation on managed fields may increase carbon accumulation on land, relative to the unfertilised system, and grazing by domestic animals may also affect trace gas fluxes. CO fluxes may be affected due to changes in soil temperature and moisture. These effects on trace gas fluxes, however, are highly speculative and remain a research issue.

- **Methane from termites attributable to biomass left to decay**

  When forests are cleared, a portion of the cleared biomass may be left to decay on the ground. Frequently some of the biomass decay is accomplished by termites which emit both methane and carbon dioxide during this process. Fearnside (1990b) estimates that 75 per cent of the unburned carbon is decomposed by termites, and of this 75 per cent, 99.8 per cent is released as CO_2 and 0.2 per cent is released as CH_4. Fearnside suggests that forest clearing results in increased termite populations and thereby enhances natural termite CH_4 emissions. However, as discussed by Collins and Wood (1984), data from Malaysia, Nigeria, and Japan indicate that clearing and cultivation in some forests reduces termite populations. The only incidence of termite abundance increase following clearing cited by Collins and Wood was entirely due to a fungus-growing termite, a type of termite which is unlikely to produce methane. Because of the uncertainty of the effect of clearing on termite populations and associated CH_4 release, no guidance on calculation of this component is included in the methodology.

- **Soil carbon loss in tropical systems**

  The basic calculations allow but do not encourage estimation of soil carbon loss after clearing of tropical forests. There are research results which indicate that conversion of tropical forests to pasture may or may not result in loss of soil carbon.[36] Because of the uncertainty no recommendation is made in the basic method concerning whether and how to estimate this component. Further research appears needed to resolve this issue.

- **Fate of roots in cleared forests**

  The basic calculation ignores the fate of living belowground woody biomass (roots, etc.) after forest clearing. The amount of belowground biomass affected, and its fate, need to be considered as work continues beyond the basic calculations. This belowground biomass could be treated as slash but with perhaps a longer decay time. Alternatively, it might be more reasonable to deal with the belowground biomass in conjunction with soil carbon calculations, as both are likely to involve long time horizons. This is an area for further development by the relevant expert groups, and also by national experts in individual countries who are encouraged to carry out experimental calculations. See Box 8 for further information on the estimation of the amounts of belowground biomass.

- **Aboveground biomass after conversion**

  In the basic calculation, a single default value (10 tonnes dm/ha) is recommended for aboveground biomass which regrows after forests are cleared for conversion to crops or pastures. This may be somewhat variable depending on the type of crop or other vegetation which regrows. National experts carrying out more detailed assessments may wish to account more precisely for this variability.

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[36] See, for example, Fearnside (1980, 1986); Bushbacher (1984); Cerri et al. (1988); and Lugo et al. (1986). Keller et al. (1986) indicate that clearcutting of tropical forests does not appear to release soil carbon.

Box 8
BELOWGROUND BIOMASS

For forest clearing, carbon in belowground (root) biomass is ignored in the basic calculations, but should be considered. There are large uncertainties concerning the time horizon over which this biomass would oxidise. As noted in the text, it could be considered with decay of slash left aboveground, or with soil carbon in the calculations of CO_2 emissions from forest conversion. There is no recommended step-by-step methodology for calculating the carbon released from this source in the current guidelines. However, interested national experts are encouraged to carry out such calculations and report them to the IPCC using their own methods. The following information and references could be useful to experts working in this area.

- Brown, et al. (in press) provide the following multipliers to be applied to total aboveground biomass in order to estimate the belowground biomass for tropical regions:

lowland and montane dry forests	0.5
lowland and montane seasonal forests	0.1
lowland and montane moist forests	0.18

- Cooper, C.F. (1993) gives multipliers for temperate forests:

conifers	0.20
hardwoods	0.25

Estimation of CO_2 emissions from belowground biomass after clearing has been identified as an area of future work.

Abandoned Lands

The basic calculations account only for the portion of abandoned lands which regrow toward a natural state. There may be additional releases of carbon from abandoned lands which continue to degrade. Where data are available, analysts doing detailed assessments may wish to account for this phenomenon.

5.3.3 Other Possible Categories of Activity

Several other land use activities affect the flux of carbon dioxide and other trace gases between the terrestrial biosphere and the atmosphere. Shifting cultivation may now be reducing the storage of carbon in forests, because of shorter fallow periods, and thereby becoming a net source of CO_2 to the atmosphere. The changing areas and distribution of wetlands may be adding to or reducing the methane burden of the atmosphere. These issues are complex; often the sign of the flux is not even known, and simple models may not give reasonable results. In this section, some of the issues and possible methodological approaches are recorded; however, an agreed-upon methodology is not yet at hand.

Shifting Cultivation

Shifting cultivation, or slash-and-burn agriculture, is a common agricultural practice in the tropics in which short periods of cultivation (usually about 3 to 5 years) alternate with longer periods of fallow (about 10 to 50 years). Clearing occurs by initial cutting and felling, followed by a series of burns. When practised in the traditional manner, shifting cultivation produces essentially no net CO_2 emissions because the forest is allowed to return to its original biomass density during the fallow period.[37] However, increasing population pressure has reduced the lengths of fallow periods so that currently much of the fallow land is not allowed to recover and net CO_2 emissions are believed to result (Myers, 1989; and Houghton, 1991). Loss of soil carbon also may occur during shifting cultivation, although the loss is certainly far less than for permanent cultivation.

Calculation of net emissions due to shifting cultivation requires calculation of average annual emissions due to clearing of forests for cultivation, and calculation of average annual uptake due to abandonment of cultivated lands in the fallow period of the shifting cultivation cycle. This involves monitoring a large number of small parcels of land over time and probably requires a model to do the book keeping.

The basic concepts are not difficult. The carbon calculations would proceed almost exactly like the deforestation and abandonment terms in the basic methodology; however, the difficulty is that the abandonment period may be shorter, and this may only be apparent by using a cohort-based model and a finite stock of forest. In other words the increasing rate of shifting cultivation (the likely data) will force a shorter fallow period and hence less regrowth, and this dynamic may only become apparent when one models the shifting cultivation cycle within a specific area of available forest.

One intermediate simple approach is to split the calculation into the two logical components. The deforestation component would be treated similarly to the basic calculations; namely, convert the above ground dry biomass[38] to carbon (multiply by 0.45) and assume 90 per cent of this material is released as CO_2 less the amount taken upon by the replacing crops (default value of 10 tonnes dm per hectare). In this intermediate step one ignores soil carbon and history since the abandonment period follows so quickly upon deforestation. To calculate the uptake of carbon by the regrowing forest during the fallow cycle, simply estimate the amount of land in abandonment (but not yet in steady-state) and the average rate of carbon accumulation per unit area in these fallow lands. The difference would be the net flux of CO_2 associated with shifting cultivation. For the biomass burned in shifting cultivation, non-CO_2 gases (N_2O, CH_4, NO_X, CO) should be calculated as described in the Forest and Grassland Conversion section above.

Flooding and Wetland Drainage

Land Flooding

Flooding of lands due to construction of hydroelectric dams, or other activities, results in emissions of CH_4 due to anaerobic decomposition of the vegetation and soil carbon that was present when the land was flooded, as well as of organic material that grows in the floodwater, dies, and accumulates on the bottom. The methane emissions from this source are highly variable and are dependent on the ecosystem "type", and the status of the ecosystem, that is flooded (i.e., above- and below-ground carbon, plant types, whether any pre-flooding clearing occurred, etc.) and on the depth and length of flooding (some regions may only be flooded for part of a year). Rates of methane emissions from freshwater wetlands are also strongly dependent on temperature, and therefore vary seasonally, as well as daily. Net emissions of N_2O and CO also may be affected by this activity, although these fluxes are not well determined.

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[37] Actually, following the first clearing (i.e., clearing of primary forests), the forest biomass may not recover fully to its original density during the fallow period, but instead reaches a slightly reduced level, referred to as a secondary forest. After this point, however, clearing (of a secondary forest) is balanced by recovery (to a secondary forest), and net CO_2 emissions over time are zero.

[38] Generally, shifting cultivation is practised in fallow forests, since the least dense and most accessible forest areas are most susceptible to this form of clearing. Aboveground biomass density estimates for fallow forests are highly uncertain, and vary significantly both within and among countries because of varying ecosystem types as well as varying intervals between clearings. As a rough estimate, 50 per cent the biomass estimates for unproductive forests can be used (see Table 5-2 for regional estimates). Biomass densities for other forest types, e.g., undisturbed forests, should of course be used if more appropriate in specific cases.

A straightforward methane flux calculation can be based on the area of land flooded, due to hydroelectric production or other manmade causes, an average daily CH_4 emission coefficient, and the number of days in the year that the area is flooded. Since measurements of CH_4 emissions from freshwater wetlands are so variable, both spatially and temporally, the area should be divided into groups based on characteristics such as length of flooding, vegetation type, and latitude. Then appropriate emission coefficients can be chosen for each group, rather than choosing one emission coefficient for the entire area of flooding. Table 5-8 presents average daily CH_4 emission rates for natural wetlands, derived from measured emission rates in field experiments, and average CH_4 production periods based on data on monthly mean temperatures and inundation lengths. These rates and production periods can be used if countries do not have more appropriate estimates.

TABLE 5-8
AVERAGE METHANE EMISSIONS AND PRODUCTION PERIODS OF NATURAL WETLANDS

Wetland Categories	Emission Rate (mg CH_4-C/m^2/day)	Production Period (days)
Bogs	11 (1-38)	178
Fens	60 (21-162)	169
Swamps	63 (43-84)	274
Marshes	189 (103-299)	249
Floodplains	75 (37-150)	122
Lakes	32 (13-67)	365

Source: Aselmann and Crutzen, 1989.

Note: Average daily emission rates are derived from measured emission rates in field experiments (the range in measured emission rates is in parentheses after the average), and average production periods are based on monthly mean temperature data and lengths of inundation.

Wetland Drainage

Freshwater wetlands are a natural source of CH_4, estimated to release 100-200 Tg CH_4 (75-150 Tg CH_4-C) per year due to anaerobic decomposition of organic material in the wetland soils (Cicerone and Oremland, 1988). Destruction of freshwater wetlands, through drainage or filling, would result in a reduction of CH_4 emissions, and an increase in CO_2 emissions due to increased oxidation of soil organic material (Moore and Knowles, 1989). The magnitude of these effects is largely a function of soil temperature and the extent of drainage (i.e., the water content of the soil). Also, since dryland soils are a sink of CH_4, drainage and drying of a wetland could eventually result in the wetland area changing from a source to a sink of CH_4 (e.g., Harriss et al., 1982).

Loss of wetland area could also affect net N_2O and CO fluxes, although both the direction and magnitude of the effect is highly uncertain. Natural dryland soils are a source of N_2O, believed to emit 9-28 Tg N_2O (3-9 Tg N_2O-N) annually as a result of nitrification and denitrification processes (Seiler and Conrad, 1987). This emission estimate is highly uncertain, however, as emission measurements vary both temporally and spatially by up to an order of magnitude. Moreover, the measurements are not consistently correlated with what are believed to be controlling variables such as soil temperature, moisture, and composition, and vegetation type. Dryland soils both produce and consume CO. Carbon monoxide production, estimated at 2-32 Tg CO (1-14 Tg CO-C) per year, is an abiotic process due to chemical oxidation of humus material (Seiler and Conrad, 1987). It is strongly dependent on soil temperature, moisture, and pH. Destruction of CO is a biological process believed to be due to micro-organisms present in the soil. Carbon monoxide destruction (250-530 Tg CO/yr, or 107-227 Tg CO-C/yr) increases with increasing temperature, although it is independent of soil surface temperature (indicating that the process is more active in deeper soil layers) and requires a minimum soil moisture (Seiler and Conrad, 1987). Desert soils have always been found to be a net source of CO, as have savanna soils, at least during the hottest parts of the day. CO destruction outweighs production in humid temperate soils; humid tropical soils are believed to also be a net sink of CO because of their higher soil moisture and lower soil temperature than deserts and savannas.

To calculate the reduction of CH_4 emissions due to wetland drainage, the area drained is multiplied by the difference in the average daily CH_4 emission rate before and after draining, and is multiplied by the number of days in a year that the wetland was emitting CH_4 prior to drainage. The number of days of CH_4 emissions prior to drainage can be approximated by using the number of days in the year that the wetland was flooded. To calculate the increase in CO_2 emissions due to this activity, the area drained is multiplied by the difference in the average annual CO_2 emission rate before and after draining. This assumes that the elevation in CO_2 emissions due to drainage continue throughout the year. However, the length of time over which the elevated CO_2 emissions continue is uncertain – it could be less than a year; it could be greater than a year. The net release would also depend on the degree to which there was regrowing vegetation, a CO_2 sink.

In summary, the difference in CH_4 and CO_2 emissions before and after drainage will vary depending on factors such as soil temperature, extent of drainage, and wetland type. Very little data are available on this subject. A laboratory experiment with materials representing a fen, a bog, and a swamp found that the reduction in CH_4 emissions increased with increasing drainage, although the magnitude of the reduction varied between the three types of materials. CH_4 emissions from the fen decreased from about 21 mg CH_4-C/m^2/day (with the water level about 10 cm above the surface) to about 0.8 CH_4-C/m^2/day (with the water table about 70 cm below the surface); CH_4 emissions from the swamp decreased from about 9 to about 0.6 CH_4-C/m^2/day; and CH_4 emissions from the bog decreased only slightly, from about 0.7 to about 0.6 mg CH_4-C/m^2/day. CO_2 emissions from all three materials were about 0.08 mg CO_2-C/m^2/day (with the water level about 10 cm above the surface), and increased to about 2 mg CO_2-C/m^2/day (with the water table about 70 cm below the surface).

The direction and magnitude of the effects on these gases are highly uncertain and significant advances in our understanding of the biological processes as well as determination of the areal extent of the activities will be required before these calculations can be adequately accomplished. It may be possible to include methane calculations associated with land flooding in early refinements of the calculations, but the N_2O and CO calculations are more difficult and as yet of uncertain importance.

Surface Waters

Some national experts have pointed out that changes in surface waters due to human activities can result in sequestration of carbon, and presumably other emissions or removals. An example is pollution of lakes due to run off, which can cause eutrophication, increasing the carbon content of waters. Pollution of coastal waters could also have similar effects. No data have been obtained thusfar to indicate whether the carbon sequestration effects of such changes are large enough to be significant. However, it is possible that some countries may want to carry out preliminary calculations and report these as part of the ongoing methods development effort.

These changes in surface waters are generally a result of combined effects including land use changes, agricultural practices, wastewater treatment, etc. in the surrounding area. Thus, they do not fit neatly into any of the broad economic sectors which form the fundamental structure of these *Guidelines*. If national experts consider the changes in surface waters to be primarily a function of land use changes, the results of preliminary calculations could be reported in the "Other" subcategory within the Land Use Change and Forestry category. Alternatively, they could be reported under Waste, Agriculture, or the newly created general "Other" category.

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T5 TECHNICAL APPENDIX: DEFORESTATION DATA

Data on rates of deforestation[39] are essential for calculating the fluxes of carbon dioxide and other trace gases between terrestrial systems and the atmosphere. When arranged on a country-by-country basis, these data provide the forcing function for computation of country-specific emissions from forest clearing. Recognising that such data sets are not yet available for many countries with the accuracy needed for these computations, this technical appendix provides suggestions for utilising the available global and national sources of data, while bringing new or better sources of information into the calculations when and where they are available.

T5.1 Food and Agriculture Organization (FAO) Published Data

Currently, the most comprehensive international source of data on rates of deforestation broken down to the country level is maintained by the FAO in the following forms:

1. Source data, preferably in the form of a time series, collected in co-operation with member countries (i.e., without standardisation) including data on: forest cover, ecofloristic zone and sub-national boundaries, biomass, plantations and conservation, collected and compiled in the form of a geographic information system.
2. Standardised estimates of forest cover, rate of deforestation, afforestation, and biomass/ha at the country level. Standardisation is done by FAO because of variations from country to country in:
    - -the definitions of "forest", "deforestation" and "afforestation"; and
    - -the reference years for forest cover and deforestation measurements.

    The standardisation is intended to bring country data to common definitions of forest cover and reference data, and to make the country information useful for regional and global studies. The basis for standardisation is adjustment functions by ecological zones based on time-series data on forest cover of countries.
3. Data from a global sample survey of forest cover state and change during 1980 and 1990 based on a limited sample of high resolution satellite images using common definitions and measurement techniques. The main aim of this survey is to calibrate regional and global estimates and provide comprehensive information on various types of on-going forest cover changes, in the form of change matrices (1980 and 1990). It should be noted that the sample survey is not intended to check or replace country estimates, but only to provide reliable estimates (i.e., with standard error) of forest cover and rate of change at regional/global levels. This is being done taking into account the inherent limitations of aggregating heterogeneous country data at regional/global levels.

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[39] This appendix is limited to discussion of current and future international sources of data on rates of deforestation at the national level. It is understood, however, that other types of input data are also key sources of uncertainty in calculations and are also the subject of a great deal of ongoing activity. These include other types of land use change and land cover data as well as more detailed information on growth rates and biomass densities for different types of forests and other ecosystems.

The results of these data collection and analysis efforts are provided in a series of publications produced by the FAO. These data can be used to construct national input data for calculating CO_2 from deforestation. These should be useful to many countries at least as a point of comparison with locally available data sources, and may be used to provide a first order estimate of national emissions if desired by national experts.

The FAO Forest Assessment produced in the early 1980s (FAO/UNEP 1981, Lanly 1982) provides a first-order estimate of deforestation rates world-wide. These data produced on a country basis can be used as a baseline land use rate. An interim assessment (FAO 1988) provided deforestation rates by country for the period 1981-1985. A 1990 assessment has been recently published (FAO 1993), which provides estimates of deforestation rates by country for the period 1981-1990. Thus, some estimates of current and historical rates of deforestation on a country basis can be obtained from these published reports. More detailed information, including sub-national data, can be obtained by contacting the FAO directly.

It should be noted, however, that there have been controversies and disagreements regarding FAO estimates of national deforestation rates at times. In some cases where national experts have developed significantly more detailed approaches for their own countries, results have been found to be significantly different than the published FAO estimates. (See, for example, Fearnside et al., 1990*b* for Brazil). Any internationally provided data should be reviewed carefully by national experts if they are used as a basis for emissions inventory estimates.

Some countries have well-developed estimates of deforestation, based on very good measurements, which provide more detail than is available from the FAO assessments (e.g., Arbhabhirama et al., 1987; INPE, 1992). Where detailed national studies exist for the early 1990s they may be a preferred data source for experts preparing national inventories. FAO data may nonetheless be useful for comparison purposes. The choice of input data is always ultimately a decision of the national experts.

Lack of consistent time-series data at *national level* is considered by FAO staff to be the most critical problem in estimating the deforestation rate. Variation in definitions and measurement techniques from country to country is another problem in making regional and global estimates. FAO has initiated a comprehensive programme for capacity-building in forest resources assessment by mobilising technical and economic co-operation among member countries and among concerned regional and global agencies as follow-up to recommendations of UNCED Agenda 21: Programme Area D.

T5.2 Ongoing Data Efforts

The lack of a comprehensive data set on deforestation rates is a critical problem. The development of such data sets remains one of the priorities for the IPCC process in the coming years (IPCC 1992). Methods using high resolution remote sensing in conjunction with geographic information systems appear most promising. The International Geosphere-Biosphere Programme's Data Information System (IGBP-DIS) is serving as a central focal point to collect and disseminate information about the various ongoing activities and data sets dealing with land use and changes in land cover. The IGBP-DIS is located in Paris, France (Tel: 33-1-4427-6168, Fax: 33-1-4427-6171).

Experts from around the world have begun to build the scientific, technical, and procedural underpinnings of such a system. The World Forest Watch Meeting held in Sao Jose dos Campos, Brazil (June 1992) provided a high-level international forum for the assessment of current approaches to satellite-based forest monitoring. This meeting also served as a basis for forwarding recommendations from the technical and scientific communities to the policy makers and government leaders at UNCED.

A variety of international participants were represented at the World Forest Watch Conference. The conference concluded that significant technical and methodological advancements have been made in recent years, and they are now sufficient for proceeding with an observation system which could satisfy both scientific and national-level forest management requirements. A priority action now is to establish a fully functional, permanent monitoring system. The system would support national forest management, global change science, and international policy information needs, such as those of the IPCC.

The current research and development being carried out in laboratories and research centres around the world has shown that it is now feasible to acquire repetitive satellite data sets over very large areas, and that the information derived from such data sets can form the core of a global forest monitoring program. The International Space Year / World Forest Watch Conference has recently provided illustrations that space observation technology and the community of users are ready for regional and global applications.

Progress made on two forest monitoring projects is worth noting in this respect.

1 The National Institute for Space Research (INPE) of the Secretariat of Science and Technology of the Presidency of the Republic of Brazil has made surveys of the entire Legal Amazon (about 5 million square kilometres) using LandSat images. This survey was first conducted in 1978 (with 1977 and 1979 being used to cover areas covered by clouds in the 1978 imagery). The studies were repeated in 1988, 1989, 1990 and 1991. These space-based surveys mapped the extent of gross deforestation (i.e., without accounting for forest regeneration or the establishment of plantations) in the portion of the Legal Amazon covered by forest. The ecosystems ranged from dense tropical forest to thick savannas (cerradao) with a total surface area between 3.9 and 4 million square kilometres. The 1978 survey used 232 Land Sat MSS black and white images based on channels 5 and 7 at a scale of 1:250,000. The more recent studies used 229 LandSat TM images annually in a colour composite of channels 3,4 and 5 at a scale of 1:250,000.

2 In 1990 NASA, in conjunction with the United States Environmental Protection Agency and the US Geological Survey, began a prototype procedure for using large amounts of high resolution satellite imagery to map the rate of tropical deforestation. This activity, the LandSat Pathfinder Project, builds on experience gained during a proof-of-concept exercise as part of NASA's contribution to the International Space Year/World Forest Watch Project. It focused initially on the Brazilian Amazon, and has now been expanded as part of NASA's Earth Observing System activities to cover other regions of the humid tropical forests.

This project has succeeded in demonstrating how to develop wall-to-wall maps of forest conversion and regrowth. The project is now in the process of extending its initial proof-of-concept to a large-area experiment across Central Africa, Southeast Asia and the entire Amazon Basin. The project is acquiring several thousand LandSat scenes at three points in time - mid 1970s, mid 1980s, and mid 1990s - to compile a comprehensive inventory of deforestation and secondary growth (regrowth of forests on land cleared and subsequently abandoned) to support global carbon cycle models. Methodology and procedures have been identified. Although this exercise is being implemented for most of the tropics, it is not an operational global program. In principle it will provide an initial large-scale prototype of an operation program.

> The use of geographic information system technology is crucial to the project, as it provides the overall framework upon which the raw satellite data can be synthesised with other cartographic, numerical, and geographical data for scientific research and national forestry management. As its name implies, this project is exploratory, but it could readily be expanded to form the nucleus of a global scale operational program.

These two projects demonstrate the feasibility of developing a global tropical forest information system to support an operational tropical forest monitoring program. High resolution satellite data from LandSat or Spot satellites are being used to provide digital maps of deforestation.

High resolution data from the LandSat series of earth observation satellites can be employed to make regular measurements of deforestation. Large amounts of these data exist in national and foreign archives, dating back approximately 20 years. This satellite data system has been perfected over years of development (5 satellites have been launched) and it is expected to be an operational system into the next century (LandSat 7 and 8 are being designed[40]). This system is complemented by the French SPOT satellites. Thus, a continuous and consistent source of data is available upon which a high resolution, fine-scale (1:250,000 scale mapping) information system could be developed.

An operational forest monitoring using high resolution data such as that provided by LandSat and SPOT could provide wall-to-wall mapping for the entire tropical zone. The approach would be as follows:

- An initial mapping effort would define where and how much deforestation exists in the tropical forests (a baseline assessment). The stratification of forest types and critical regions could be enhanced by the use of coarse resolution information from AVHRR.
- Acquisition of LandSat and/or SPOT imagery can be co-ordinated regularly every 3-5 years to obtain cloud-free coverage systematically throughout the tropics. The best way to achieve this is to rely heavily on the foreign ground stations. For example, from the LandSat routine and complete coverage for the Amazon Basin and Southeast Asia is possible from several foreign ground receiving stations in these regions. As a rule these stations regularly collect data from every orbital pass within the line-of-sight radius of their antenna. For regions, such as central Africa where no ground station exits, programmed acquisitions from the satellite are possible.
- The imagery are analysed for deforestation using a methodology analogous to that developed by the LandSat Pathfinder Project, where a simple delineation of the boundary between intact forest and cleared areas is recorded into a geographic information system. Areas of secondary growth would also be delineated. Subsequent years are compared to the baseline and the increment of new deforestation and secondary growth is recorded. The resulting data set provides a 1:250,000 to 1:500,000 scale map of deforestation at a regular repeat interval, and from this a rate of deforestation is derived.
- These geographically-referenced measurements can directly support the implementation of the IPCC national inventory methodology, which requires a time series of historical forest clearing data, and would require updating at periodic intervals. The proposed accurate and precise deforestation data set would be an important asset to national experts working to implement the IPCC methodology for national emissions and removals from land use change.

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[40] Landsat 6 crashed, soon after it was launched.

- An accuracy assessment effort will need to be put into place to define and track the measurement variance and error. This component will need to determine accuracy with respect to: (a) variance due to positional accuracy (i.e., the mapping precision) and (b) the variance associated with image interpretation.
- An effort focused on establishing in-country co-operation will be necessary. Such co-operation fulfils several ancillary but vital objectives: (a) it builds a process of national acceptance of the methods and results through active involvement, (b) it provides a mechanism for technology transfer and training for eventual implementation of national inventories based on remote sensing, (c) it facilitates logistical co-ordination of the field component, (d) it provides direct co-operation at various foreign ground stations, and (e) it enables co-operation with national and regional experts in the interpretation of imagery.

T5.3 Summary

Tropical deforestation and carbon emissions are important components of both science and policy. Yet, in spite of the growing need for precise estimates of deforestation to support both international policy and basic research, an operational program of measurement, monitoring and mapping has yet to be developed. Comprehensive and systematic information on the extent of forest and forest loss is not available on a global basis. The latest IPCC Assessment Report, for example, considers the rate of tropical deforestation to be one of the key unknowns in global climate change assessment. Any lasting and effective implementation of a global system of national emission inventories to support the IPCC and other international processes will require a new, concerted effort to measure and map tropical deforestation, and develop the data base necessary for other important components of the calculations. These measurements of deforestation from high resolution satellite remote sensing can also support the UN/FAO Forest Assessment by providing quantitative and spatially comprehensive measures of changes in forest cover for the tropics.

This Technical Appendix summarises the most comprehensive current data sources for tropical deforestation information, and discusses ongoing efforts to improve on this data via analysis of remote sensing images. Ideally, each country would like to have data on their land use changes and associated trace gas emissions and uptake over the past 40 to 50 years so that their estimates of current annual net emissions would include delayed and continuous emissions and uptake due to activities that occurred in prior years. Since this is not the case for many countries, the methodology described has made simplifying assumptions in order to treat the effects of past land use activities on current emissions. This appendix provides some perspective on the available international sources for dealing with one key data gap – data on rates of forest clearing over time.

In future editions of the *Guidelines*, it may be possible to include more information on data available to assist national experts as a result of some of the ongoing efforts described in this version. It may also be possible and desirable to provide similar discussion of a range of other international data collection efforts which may assist national experts in refining other key data driven uncertainties in the national estimates of emissions and removals from land use change and forestry.

In the meantime, it is recommended that countries continue efforts to collect historical records of land use change and develop systems of tracking land use through time so that as the methodology is further refined, the land use change time series needed to account better for emissions and uptake of carbon dioxide and other trace gases are available.

6 WASTE

6.1 Overview

Disposal and treatment of industrial and municipal wastes can produce emissions of most of the important greenhouse gases (GHG). Solid wastes can be disposed of through landfilling, recycling, incineration, or waste to energy. GHG emissions from waste to energy, where waste material is used directly as fuel or converted into a fuel, should be calculated and reported under chapter 2: Energy. Liquid wastes can be dealt with through various forms of wastewater treatment. In addition, sludge from wastewater can be incinerated. This chapter will deal with emissions resulting from landfilling of solid waste, treatment of liquid wastes, and waste incineration.

The most important gas produced in this source category is methane. Significant amounts of the annual global methane produced and released into the atmosphere are a by-product of the anaerobic decomposition of man-made waste. Two major sources of this type of methane production are landfills and wastewater treatment. In each case, methanogenic bacteria break down organic matter in the waste to produce methane. These sources are treated in detail in later sections of this chapter.

Landfilling of solid waste represents the major form of solid waste disposal in the industrialised world (OECD, 1993). In addition to CH_4, landfills also can produce substantial amounts of CO_2 and non-methane volatile organic compounds (NMVOCs). CO_2 is primarily from decomposition of organic material derived from biomass sources (e.g. crops, forests) which are regrown on an annual basis. Hence, these CO_2 emissions are not treated as net emissions from waste in the IPCC methodology. If biomass raw materials are not being sustainably produced, the net CO_2 release should be calculated and reported under the Agriculture or Land Use Change and Forestry sections.

The process of wastewater treatment produces NMVOCs as well as CH_4 (EEATF, 1992). Wastewater treatment is also now being studied as a source of N_2O. Norway (IPCC, 1993), the Netherlands (Kroeze, 1994), Belgium (Debruyn et al., 1994) and Japan (Kyosai and Mizuochi, 1993) have documented N_2O production from their sewage treatment processes. Future evaluation of ongoing research will give an indication of the importance of this source. The effluent of wastewater treatment plants and all other waste that is disposed of in surface water can lead to methane and nitrous oxide emissions from inland and coastal waters. The same applies to untreated sewage or excess manure and fertiliser application. Runoff can lead to surface water pollution and related methane and nitrous oxide emissions. Methane emission from polluted surface water have not yet been estimated by countries. Future research will give an indication of the importance of this source. Nitrous oxide emission from polluted surface waters have been estimated in the Netherlands (Van Amstel (ed.), 1994), and were 10 kt on a total national emission of 60 kt N_2O. Eutrophication can lead to algae blooms and storage of carbon when deposited on the bottom of lakes, coastal waters and ditches.

Waste incineration, like all combustion, can produce CO_2, CH_4, CO, NO_x, N_2O and NMVOCs. No detailed methodologies are provided for this source category. Instead, the section on waste incineration later in this chapter provides references to other major methods documents already available for some gases. For CH_4 and N_2O it is only possible to report preliminary estimates and research results at this time. Further studies are needed to give more information about GHG emissions from this source category.

The sections in this chapter dealing with land disposal of solid waste and wastewater treatment give background information on the source, a description of a methodology to estimate methane production only, and uncertainties associated with estimating emissions. This is consistent with the initial priorities under the IPCC methodology programme. National experts are encouraged to report any other relevant emissions for which data are available, along with documentation of methods used. This will greatly assist in the development of more complete methods for future editions of IPCC *Guidelines*. For information on estimation procedures and emissions factors for other GHGs which are currently not provided in this chapter, experts should consult extensive existing literature developed by other emissions inventory programmes. Some key examples are:

- Default Emission Factor Handbook (EEATF, 1992);
- Joint Emission Inventory Guidebook (CORINAIR/EMEP, 1995 forthcoming);
- US EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Supplement F (AP-42) (US EPA, 1993*a*);
- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1985);
- Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines (US EPA, 1991*a*).

6.2 Methane Emissions From Land Disposal of Solid Waste

6.2.1 Introduction

Since the early 1980s, it has been recognised that the methane component of landfill gas can be a local environmental hazard if precautions are not taken to prevent uncontrolled emissions or migration into surrounding land. Gas can migrate from the landfill either laterally or by venting to atmosphere, and this can cause vegetation damage and unpleasant odours at low concentrations, while at higher concentrations the gas may form explosive mixtures.

More recently, increasing attention has focused on the role of methane in global atmospheric change. Methane from landfills contributes a significant proportion of annual global methane emissions, although the estimation is subject to a great deal of uncertainty. Estimates of global methane emissions from landfills range from 20 to 70 Tg/yr, global anthropogenic sources emit about 360 Tg/yr, which suggests that landfills may account for 6 to 20 per cent of the total. (IPCC, 1992)

This section will describe the processes that result in gas generation from land disposal of solid waste and the factors which affect the amount of methane produced. It will then describe methodologies for estimating methane emissions from landfills. One of these methods is proposed as a default base method with which all countries can comply. Other methods are also described as well as some examples from various countries that have applied them. The section also discusses an approach to estimating CH_4 from open dumping, which is based on a limited understanding of this source activity. Finally, the section also discusses sources of uncertainty associated with any estimates of methane emissions from landfills, in particular the availability and quality of data required.

6.2.2 Land disposal gas generation

Organic waste in land disposals is broken down by bacterial action in a series of stages that result in the formation of methane and carbon dioxide (termed biogas or landfill gas) and further bacterial biomass. In the initial phase of degradation, organic matter is broken down to small soluble molecules including a variety of sugars. These are then broken down further to hydrogen, carbon dioxide, and a range of acids. These acids are then converted to acetic acid which, together with hydrogen and carbon dioxide, forms the substrate for growth of methanogenic bacteria.

Land disposal sites are by nature heterogeneous. Research has focused on landfills and all microbiological investigations into site characteristics have shown that there are considerable differences between different landfills and even different regions within the same landfill (Westlake, 1990). This makes it very difficult to extrapolate from observations on single landfills to predictions of global methane emissions. Nevertheless, there are a number of significant factors which influence the generation of methane from land disposal of solid waste. A better understanding of these factors can reduce the uncertainty associated with emissions estimates.

6.2.3 Factors influencing methane production in land disposal of solid waste

The factors which influence methane production have been reviewed comprehensively elsewhere (e.g. Peer et al., 1993; US EPA, 1992; US EPA, 1991*b*; US EPA, 1991c; Lawson and Alston, 1990; Augenstein and Pacey, 1991). Therefore this section will only provide a brief summary of the most significant factors relating to methane emissions.

Waste management practices

The two main types of waste management practices of concern for CH_4 emissions are open dumping, which is generally practised in developing regions, and sanitary landfilling, generally practised in developed countries and urban areas of developing countries. Both of these types of waste management can result in methane production if the waste contains organic matter.

Aerobic waste treatment and composting of solid waste can increase the soil organic matter. Emissions of methane and nitrous oxide from this activity are thought to be low. Because such practices can increase soil carbon, an analysis of aerobic waste treatment should also consider the impact of this practice on GHG emissions from agricultural soils.

In **open dumping**, wastes are disposed of in shallow, open piles, generally only loosely compacted, and with no provision for control of any pollutants generated, either gas or leachate. Scavenging by animals and humans can remove much of the biodegradable wastes therefore reducing substrate availability.

Wastes in open dumps generally decompose aerobically, producing carbon dioxide. However, there is anecdotal evidence that some methane production can occur (Thorneloe et al., 1991), but this has not been systematically quantified. Methane from open dumping is therefore not included in any methodology considerations for global inventories. Bhide et al. (1990) reported biogas recovery from two uncontrolled landfills in Nagpur, India. The CH_4 content of the biogas from one site was 30 to 40 per cent. This suggests that open dumps are a source of CH_4.

Thorneloe et al. use the same methodology to calculate CH_4 emissions from open dumping in non-industrialised countries as from sanitary landfills in industrialised regions. However, total CH_4 emissions are reduced by 50 per cent to account for the differences between CH_4 production potential from open dumping and sanitary landfilling. The choice of 50 per cent is acknowledged to be arbitrary and should be updated when additional data are available.

Sanitary landfills are designed specifically to receive wastes. Landfill design and management is becoming increasingly sophisticated in many countries, as the serious environmental consequences of uncontrolled landfilling are becoming understood. New landfill design standards in many countries are ensuring that landfills are lined before receiving waste, and also that there are adequate provisions for the safe control, and removal where appropriate, of gas and leachate generated. Good waste management practices ensure that the waste is compacted to minimise use of void space, also that it is covered both with intermediate daily cover and with an effective cap when final restoration takes place. The costs associated with these management practices are encouraging the development of larger landfills to economise on scale, taking in greater quantities of waste. All of these factors can encourage the rapid development and maintenance of anaerobic conditions within the landfill, and hence ensure continued methane production.

Waste composition

The composition of waste is one of the main factors influencing both the amount and the extent of methane production within landfills. Municipal solid waste (MSW) contains significant quantities of degradable organic matter. This can decompose to form acetate and carbon dioxide as intermediate decomposition products, which are the main substrates for methanogenic bacteria. Different countries and regions are known to have MSW with widely differing compositions: wastes from developing countries generally have a high putrescible content, whereas developed countries, especially in North America, have very high paper and card content in their MSW. Thus landfills in developing countries will tend to stabilise within 10-15 years because putrescible material decomposes rapidly, whereas landfills with a high paper and card content will tend to produce methane for 20 years or longer, at a lower rate than landfills in developing countries.

Physical factors

The moisture content of the landfill environment is one of the principal physical factors influencing landfill gas production. Moisture is essential for cell growth and metabolism, also for transport of nutrients and bacteria within the landfill. The moisture content of a landfill will depend on the initial moisture content of the waste, the extent of infiltration from surface and groundwater sources, and on the amount of water produced during the decomposition processes.

Temperature will affect the growth rate of the bacteria: Under anaerobic conditions, landfill temperatures are generally between 25-40°C. These temperatures can be maintained within the core of the landfill independent of the external temperatures. Outside of these temperatures, methane production is reduced or can cease altogether.

Optimal pH for methane production is between 6.8 and 7.2. Nutrients that are important for efficient bacterial growth include sulphur, phosphorous, sodium and calcium. CH_4 production rates decrease sharply with pH values below about 6.5 (Zehnder, 1982). When refuse is buried in landfills, there is often a rapid accumulation of carboxylic acids; this results in a pH decrease and a long time-lapse between refuse burial and the onset of CH_4 production, ranging from months to years.

> "The lapsed time preceding the onset of CH_4 production in landfills is an important aspect when considering the management of individual landfills for biogas recovery or emissions mitigation. The age at which landfills and uncontrolled dumps begin to produce CH_4 is of lesser importance when evaluating global CH_4 emissions from MSW management systems. For estimating global emissions, it is the total CH_4 production potential that is more critical." (Thorneloe, 1993*a*).

The importance of these physical factors to methane generation can be demonstrated within controlled laboratory conditions, but the heterogeneity of landfills makes definitive research very hard under field conditions, and there are limited data available. Therefore until better global data become available, none of these factors can be taken into consideration when estimating national or global methane emissions.

6.2.4 Methodologies to estimate methane emissions from solid waste disposal

A number of methods have been used to estimate methane emissions from solid waste disposal. These methods vary widely, not only in the assumptions that they make, but also in their complexity, and in the amount of data they require for the determinations.

This chapter will deal only with those methods that can be applied to whole regions or countries. There are some very complex models that are concerned with movement of methane and other gases through individual disposal sites; however these models cannot be applied to site populations and therefore will not be considered further here.

The methodology presented here applies to sanitary landfills. As discussed above, there is anecdotal evidence to indicate that open dumps should also be considered in national inventories, especially in developing countries. Although they are not managed like sanitary landfills, these dumps contain high levels of organic material which degrade rapidly over a period of about ten years. National experts may use their own discretion as to whether and how to include this category in national inventories.

No methodology has been developed as yet for open dumps, although this will be considered in future work. In the meantime, national experts may use an adjusted version of the default method for landfills, if desired. Thorneloe, et al. (1991) used the landfills method but reduced emissions by 50 per cent for open dumps. National experts should make their own judgement as to whether the 50 per cent reduction factor is a reasonable approximation for conditions in their countries. Where open dumps are large and relatively undisturbed, they may emit CH_4 very much like a landfill. In other cases, small open dumps may be disturbed by animals, burning or other factors, and produce very little CH_4. Emissions believed to be from open dumps should be reported separately from landfills, with documentation of assumptions and methods used.

Mass balance and theoretical gas yields methodologies

This is the simplest method for calculating methane emissions from landfills. It is based on a mass balance approach, and does not incorporate any time factors into the methodology. The calculation assumes that an instantaneous release of methane takes place from refuse during the same year that the refuse is landfilled.

Using empirical formulae

At its simplest level, an empirical formula for refuse can be used as the starting point for estimating yields from waste. If a complete breakdown to carbon, hydrogen and oxygen is considered, this gives very high and unrealistic levels of methane generation, therefore some adjustments are necessary because complete breakdown is known not to take place. EMCON Associates (1981) modified this by using an extended Buswell equation, which takes other elements into account, and estimated that 53 per cent of the carbon content of refuse is converted to methane. If microbial biomass as an end product is also taken into account, then this further reduces the methane generation potential. Polytechnic of East London (1992) have predicted that this results in the production of 234 m^3 of methane per tonne of wet MSW.

Default methodology: using degradable organic carbon content

A more useful approach is to consider the degradable organic carbon (DOC) content of MSW, i.e. the organic carbon that is accessible to biochemical decomposition, and to use this value to calculate the amount of methane released from the MSW. This is the approach taken by Bingemer and Crutzen (1987), who segregated the world into four economic regions, and applied different values of DOC to the waste generated within each of these regions. As a simple and robust method, this is currently the most widely accessible default methodology for calculating country-specific emissions of methane from landfills, since it requires the least amount of data to perform the calculations, and it can be modified and refined as the amount of data available for each country increases.

The four regions derived by Bingemer and Crutzen (1987) were: US, Canada and Australia; other OECD; USSR and Eastern Europe; and developing countries. In their

assessment, they determined how much MSW was produced for each region, and how much of that MSW was degradable organic carbon.

The percent degradable organic carbon (DOC) is based on the composition of waste. The percent of DOC can be calculated from a weighted average of the carbon content of various components of the waste stream. Bingemer and Crutzen (1987) collected data for the various global regions considered in the study. No data were available for the USSR or Eastern Europe or for some developing countries, so these values had to be approximated. These data were updated by OECD (1991) using more recent data from OECD (1989) where available. The data presented in OECD (1991) are summarised in Table 6-1. It is highly recommended, however, for countries where the composition of the fractions in the waste stream are known, that these be combined with a knowledge of the carbon content of these various fractions to produce a country-specific value for DOC.

TABLE 6-1
REGIONAL WASTE DISPOSAL, COMPOSITION, AND WASTE GENERATION DATA

Region	MSW Landfilled Fraction	DOC of MSW Fraction	Waste Generation (kg/cap/day)
US/Canada/Australia	**0.91**	0.22	**1.8**
US	0.62	NA	2.0
Canada	0.93	NA	1.7
Australia	0.98	NA	1.9
Other OECD	0.71	0.19	**0.8**
Japan	0.28	NA	0.9
New Zealand	0.95	NA	1.8
Austria	0.57	NA	0.6
Belgium	0.50	NA	0.9
Denmark	0.63	NA	1.2
Finland	0.87	NA	1.1
France	0.47	NA	0.7
Germany	0.69	NA	0.9
Greece	1.00	NA	0.7
Ireland	1.00	NA	0.9
Italy	0.35	NA	0.7
Luxembourg	0.27	NA	1.0
Netherlands	0.55	NA	1.2
Norway	0.78	NA	1.3
Portugal	0.24	NA	0.6
Spain	0.76	NA	0.8
Sweden	0.42	NA	0.9
Switzerland	0.18	NA	1.0
UK	NA	NA	1.0
USSR/E. Europe	**0.85**	0.175	**0.6**
Developing Countries	**0.80**	0.15	**0.5**

Sources: Bingemer and Crutzen (1987) for regional data and OECD (1989) for individual countries.

The determination of annual methane emissions for each country or region can then be calculated from Equation 1:

EQUATION 1

Methane emission (Gg/yr)

=

Total MSW generated (Gg/yr) x Fraction MSW landfilled x Fraction DOC in MSW x Fraction Dissimilated DOC x 0.5 g C as CH_4/g C as biogas x Conversion ratio (16/12) - Recovered CH_4 (Gg/yr)

Total MSW generated can be calculated from Population (thousand persons) x Annual MSW generation rate (Gg/thousand persons/yr).

In developing countries only urban populations are considered, since the rural populations are assumed to dispose of their waste in very small open dumps, where significant methane generation is assumed not to occur.

Fraction of degradable organic carbon dissimilated: This is the portion of carbon in DOC that is converted to landfill gas. The assimilated fraction is the remainder of carbon that is used to produce new microbial cell material. To date, estimates of how much carbon may be dissimilated have relied on a theoretical model that varies only with the temperature in the anaerobic zone of a landfill: $0.014T + 0.28$, where T = temperature (Tabasaran, 1981). The temperature in the anaerobic zone of a landfill is thought to remain constant at about 35°C, regardless of ambient temperature (Bingemer and Crutzen, 1987). Therefore applications of the Bingemer and Crutzen (1987) method use a figure of 0.77 dissimilated DOC.

No allowance was made for any reduction in methane emissions from methane oxidation, also it was assumed that all waste decomposed anaerobically within the landfill rather than aerobically.

Using the data that they had collected, Bingemer and Crutzen (1987) estimated that global emissions of methane from landfills ranged between 30 - 70 Mt per year.

As an example, an estimate for the US can be derived as follows (based on values provided by the US EPA):

Assumptions:

Waste generated:	about 235 Tg/yr to landfills
% waste landfilled:	up to 80
% DOC:	21
% DOC dissimilated:	77
Recovered methane:	1.5 Tg/yr

These assumptions yield an estimate of:

((235 Tg/yr x 0.80 x 0.21 DOC x 0.77 Dissimilated DOC x 0.5 kg C as CH_4/kg C as biogas x 16/12) - 1.5 Tg/yr) = 19 Tg/yr

OECD (1991) also cites a study by Piccot et al. (1990) who surveyed 31 countries through literature review and personal communication, resulting in country-specific factors for MSW generation rates per capita, waste composition and percentages of waste landfilled. These values are given in Table 4 2 of OECD (1991); however they have been subject to criticism from some countries and some OECD Workshop participants who were concerned that the data may not be very representative of their countries or regions.

It is proposed that the methodology of Bingemer and Crutzen (1987) remain as the methodology that can be used by all countries to calculate methane emissions estimates from their landfills. The Workbook provides a detailed step-by-step version of this methodology as well as default values (as discussed above) for factors to be used where they are not already available from within each country.

Limitations to this methodology

However, there are limitations to this methodology which have resulted in criticism from researchers who have tried to apply it in their own countries. Some of these factors have already been highlighted above. The principal factors which cause these concerns are:

- there is no time factor involved in the calculations; also
- there is a high level of carbon converted to methane because there are no considerations of methane oxidation.

In addition, the assumption that a constant fraction (0.77) of the DOC is dissimilated, under any ambient conditions, is open to discussion. Ranges of values for dissimilated DOC may therefore be more appropriate where local information is available.

Two further factors should be incorporated into the methodology of Bingemer and Crutzen (1987) to account for concerns relating to time factors and to methane oxidation. Both of these factors and suggested modifications to account for them are now discussed further. The calculations contained in the present version of *Volume 2: Workbook* do not take these factors into account, but they may be incorporated into future versions of the *Workbook*..

Accounting for delayed release of methane: There is a lag time between placement of the waste and the beginning of methanogenesis, after which generation increases until it reaches a plateau. In the later stages of methanogenesis, gas production trails off and eventually ceases. The actual timing of the various stages of methane generation depend on the type of waste and the conditions prevalent in the landfill.

If waste of roughly the same composition were deposited at the same frequency for the number of years that it takes for the majority of carbon in that waste to decay, the assumptions of instantaneous release would not lead to an overestimation of emissions - current emissions from all the waste deposited during those years should equal the eventual emissions from the waste deposited in the current year, as calculated by Bingemer and Crutzen's equation. If, however, the rate of disposal has increased over time, the uncorrected Bingemer and Crutzen method will overstate the current year's emissions (US EPA, 1991*a*).

In many cases, the amount of waste landfilled has in fact been increasing over the past 10 to 20 years. For example, in a country with waste compositions and disposal conditions similar to those in the United States, if the annual growth in the quantity of landfilled waste is 3 per cent, then the default method can overestimate annual emissions from landfills by about 50 per cent. Recent work in the Netherlands (van Amstel, 1994) and the United States, (US EPA, 1994) has attempted to account for this by developing correction factors based on average annual growth rate of landfill waste disposal and average amount of time the waste produces methane. These examples could be used as models by interested countries. The issue has also been identified as a priority for future work with a view to possibly updating the methodology in the future.

Accounting for oxidation: Methane migrating through aerobic soil or waste can be oxidised by micro-organisms, whilst sulphate-reducing bacteria may oxidise methane in anaerobic soil or waste. However, very little is known about the extent of methane oxidation that takes place within landfills, or of the factors which influence methane oxidation (Bogner and Spokas, 1993), and there is no widely accepted estimate for the rate at which methane is oxidised after it has been generated within landfills. Factors affecting methane oxidation are known to be related to the microbiological conditions within the site, as well as the depth of the site, and its permeability. In addition, site management is likely to be important, including the characteristics of the site cap and any venting or control measures that are installed.

More sophisticated models of methane emissions include a factor related to methane oxidation. However, the factors chosen differ widely: Orlich (1990) chooses 40 - 50 per cent; Department of the Environment (1993) use a range between 0 - 40 per cent; van Amstel et al. (1993) assume 20 per cent; US EPA (1993b) use a factor of 10 per cent. A better understanding of methane oxidation is needed to provide a more reliable factor for inclusion in future models.

Based on these models, it is suggested that the estimate of methane emissions from landfills derived using the Bingemer and Crutzen methodology be reduced by 10 per cent to account for oxidation. Some consideration of the variation associated with this value may also be appropriate.

Thus by incorporating these two modifying factors, the underlying Bingemer and Crutzen approach can be adjusted to reflect more accurately landfill conditions and country-specific data. It has the added advantage that the Bingemer and Crutzen approach is very simple and easy to use, and with these additional modifications, it can provide the best model for estimating emissions in many countries. These modifications, however, have not been included in the current version of the *Guidelines*, but they may appear in later versions.

Other approaches used

For countries where more comprehensive data are available, different and more sophisticated methods may be applied to arrive at estimates of methane emissions from landfills. There have been various refinements made to Bingemer and Crutzen's approach; these are described in the next section.

Ahuja (1990) used the same approach as Bingemer and Crutzen (1987), but included a further factor in the equation, namely the percentage of MSW that is dry refuse. Methane emissions were calculated according to Equation 2.

EQUATION 2

Methane emission (Gg/yr)

=

Total MSW generated (Gg/yr) x Fraction MSW landfilled x Fraction DOC in MSW x Fraction Dry Refuse x Fraction Dissimilated DOC x 0.5 g C as CH_4/g C as biogas x Conversion ratio (16/12) - Recovered CH_4 (Gg/yr)

Again however, this approach requires application of regional factors which are subject to much uncertainty, also the value for the Fraction Dry Refuse can be open to much dispute even within a single country, let alone world-wide.

Another empirical approach was taken by Orlich (1990), who applied factors for waste generation rates per capita and for methane generation rates per tonne of waste for both developed and developing countries. These two factors were 1.0 kg or 0.5 kg per capita per day, and 180 m^3 or 60 m^3 methane per tonne for developed and developing countries respectively. Orlich (1990) also excluded any waste disposal outside of urban areas in developing countries. This method of calculation gave a global estimate of 32.9 M tonnes of methane emissions from landfills in developed and developing countries in 1990. UN population statistics were also used to estimate future emissions up to 2030.

Richards (1989) used gross domestic product (GDP) as an indicator of waste generation rates, which in turn were used to estimate methane emissions from landfills as an energy resource. Using figures of world GDP, he estimated a world waste generation value of 490 million tonnes per annum, of which about 80 per cent would be landfilled, yielding about 100 m^3 of landfill gas per tonne of refuse over about 10 years. This analysis yielded a value of global methane emissions from landfills of 9.8 - 18.3 Mt/yr.

Theoretical first order kinetics methodologies

More complex methods for estimating methane emissions from landfills acknowledge the fact that methane is emitted over a long period of time rather than instantaneously as in the former methodologies. A kinetic approach therefore needs to take into account the various factors which influence the rate and extent of methane generation and release from landfills. This approach has generally been used to calculate emissions from individual landfills, for example in the estimation of the potential of a site to generate economic quantities of landfill gas, but it can also be applied in a more general way to entire regions or countries.

Early attempts to calculate emissions using a kinetic approach were discussed by EMCON Associates (1981), the most well known and used of which is referred to as the Scholl Canyon Model. This approach modelled the "average" landfill within the region or country, and then scaled the results to take into account the total waste landfilled within the whole region or country.

A number of factors need to be taken into account in any kinetic modelling of landfill methane generation. The main factors to consider are those of waste generation and composition, environmental variables such as moisture content, pH, temperature and available nutrients, as well as information on the age, type and time since closure of the landfill (Thorneloe and Peer, 1990).

The model equation and variables included in the Scholl Canyon model are given as follows:

$$Q_{CH_4} = L_0 R (e^{-kc} - e^{-kt})$$

where:

Q_{CH_4} = methane generation rate at year t (m^3/yr)

L_0 = DOC available for methane generation (m^3/t of refuse)

R = quantity of waste landfilled (t)

k = methane generation rate constant (yr^{-1})

c = time since landfill closure (yr)

t = time since initial refuse placement (yr)

Practical applications of kinetic models

A number of countries have applied this or similar modelling approaches to their own situation:

A recent study in the **United Kingdom** (UK Department of the Environment, 1993) has used the same modelling rationale but with two different approaches to the problem of scaling the modelling to include all wastes within the UK:

(i) UK landfilled waste was treated as if it were disposed of to a single site. Model parameters were selected to represent nationally weighted average values, and an estimate of methane production from a unit of waste was made. The results were then extrapolated to the whole of the UK.

(ii) Data were collated for sites where information was available, the yield of methane was calculated for these sites, and the results were then extrapolated to waste for the whole of the UK. Average parameter values were used as above. It was necessary to assume that the sites covered contained waste types in proportions representative of all UK sites to ensure that the extrapolation was valid.

This study drew on extensive data available on the typical composition of waste from different sources (domestic, civic amenity, commercial, industrial and inert), and used this information to divide the degradable carbon pool into three categories, each with a different decomposition rate constant, representing material that decomposes at different rates. This is a similar approach to that taken by Pacey and Augenstein (1990) and Manley et al (1990). Further modifications to the model predictions included a one year time lag before the start of methane generation, as well as modifications for aerobic decomposition, microbial biomass, leachate generation and methane oxidation. Each of the factors was included in the model as a percentage decrease in methane emissions.

The results from this study provided estimates of the range of methane production per tonne of waste over all time. These were then either compiled with waste statistics, or were incorporated into sites with known data and then extrapolated to national levels, to provide estimates of methane production from MSW in the UK. The results showed a wide range of values for the amount of methane produced from MSW, between 0.6 and 5.3 Mt per year, as well as a best estimate of about 2 Mt per year. These figures have already taken reductions from gas flaring or use into account. The study emphasised that the uncertainty associated with the estimate reflected the lack of confidence in the modelling parameters.

The Netherlands have carried out a national estimate of methane emissions using a first order kinetic model applied to the whole country (Van Amstel et al., 1993). The equation used was:

$$\boxed{Q_{CH_4} = 0.8\ k\ P_0\ e^{-kt}}$$

where:

Q_{CH_4} = production of waste gas (tonnes/year)

P_0 = concentration of degradable organic matter in kg/tonne refuse

k = degradation rate constant (0.1 per year). (Country and refuse specific)

t = time after landfilling (years)

The estimate used detailed information on landfilling that has been collected for the country since 1945, a degradation rate coefficient of 0.1 per year (based on measurements of actual methane emissions at three landfills), and a degradable organic fraction of 18 per cent before 1986, and 17 per cent between 1986 and 1995. After 1995 this fraction is predicted to decrease because of recycling and separation initiatives that are aimed at reducing the organic content of waste to landfills. The calculation also assumed an oxidation percentage in the soil cover of 20 per cent and a methane concentration of

50 per cent of the landfill gas. This approach has provided an estimate of methane emissions from landfills in the Netherlands of 377 kt methane per year (range 178-576), with 25 per cent recovery. Using a simple model in a spreadsheet the changes in refuse composition can be translated into changes in input variables like P_0 and k. In the Netherlands, a reduction of methane emissions from 377 kt in 1990 to 257 kt in 2000 and 124 kt in 2010 is expected, simply as a result of reduce, re-use and recycle policies.

In **Canada**, emissions from landfills have also been calculated using the Scholl Canyon model (Environment Canada, 1992). The approach used population statistics and waste generation rates per capita, as well as collecting as much information as possible on major landfills such as the date opened and closed, waste quantities landfilled, and gas collected. The default value for methane generation used was 232 m^3/t, whilst the rate constant k was determined for specific landfill sites. Using these factors, a value of 1405 kt methane was obtained for methane emissions from Canadian landfills in 1990 (excluding any methane reductions from flaring or use). Environment Canada (1992) estimate that this value is about 22 per cent lower than one derived using the Bingemer and Crutzen (1987) methodology.

Other methodologies used

In the **United States**, a different approach has been taken to calculate methane emissions from US landfills (US EPA, 1991*b*; US EPA, 1992; US EPA, 1993*b*, US EPA, 1994*a*; Thorneloe et al., 1994). Due to the concern with the inaccuracy of predicting degradable organic carbon and the occurrence of over-prediction of gas quantities using first-order decomposition rate equations, empirical models were developed based on data collected from about 100 existing landfill gas recovery sites. The data included landfill size, quantity of waste disposed and gas recovery rates spanning a year or more, among other information.

An empirical model was developed relating flow rates to welled waste through statistical and regression analyses. (US EPA, 1991*b* and 1992; Thorneloe, 1992.) The emission factors that were developed using this approach are believed to represent the actual gas emission rates as opposed to model predictions based on assumed values for degradable organic carbon. The emission factors, as shown below, are substantially lower than factors derived for the United States from other methods, such as the Bingemer and Crutzen (1987) approach.

Bingemer and Crutzen Approach	0.15 m^3	per kilogram of waste
US Regression Approach	0.11 - 0.12 m^3	per kilogram of waste

The findings from the regression modelling approach indicate that US methane emissions account for about 10 Tg per year in 1990, and does not account for methane being used and flared. This value remains somewhat uncertain as the amount of waste disposed of in landfills in the US remains uncertain.

Using Bingemer and Crutzen's approach and similar inputs as the regression approach, an average for US emissions was 20 Tg per year (US EPA, 1994*b*), suggesting that Bingemer and Crutzen's approach overestimates the US emissions by approximately 100 per cent. This overestimation results both from the increasing quantities of wastes disposed of annually (for which the Bingemer and Crutzen method may be corrected as discussed above) and from the higher assumptions of the amount of gas emitted from decomposing carbon.

A regression approach such as that used by the United States may be appropriate to use in other countries. However, regression coefficients may vary considerably between different countries because of the many factors that differ between landfills in the United States and in other countries. In particular, the landfills included in the United States analyses were generally some of the largest landfills in the world. Few other countries have as many landfills as large as this. Other factors which will influence the value of the regression coefficient include the waste composition, site management techniques, and the climate. Other countries are conducting studies to see if similar results are found. The United Kingdom's Department of the Environment is obtaining gas extraction data from landfills and will explore a similar modelling approach.

6.2.5 Sources of uncertainty

Several sources of uncertainty in estimating emissions of CH_4 from landfills exist, these include:

- The quantity of CH_4 that is actually produced from the waste in the landfill;
- The quantity and composition of landfilled waste;
- The quantity of CH_4 that is actually emitted to the atmosphere.

Emissions of methane from older small sites

Many methods of estimating methane emissions from landfills exclude older small sites, on the grounds that emissions from these sources are very insignificant. For example, US EPA's (1993*b*) calculations have excluded any consideration of these sites contributing to methane emissions. However, there are thought to be about 30,000 older closed landfills in the United States (Thorneloe, 1992), and field measurements of urban methane concentrations indicate that older closed landfills are often significant sources of emissions in the urban environment (Kolb et al. 1992). Omission of older closed landfills from this analysis therefore biases the estimates of methane emissions downwards, contributing to the overall uncertainty in the estimate.

Waste quantities and composition

The most significant factor that determines the accuracy of estimates of methane production from landfills is an accurate knowledge of the quantity and composition of wastes disposed of to landfill. This includes the quantity of waste already in place, plus data relating to annual waste disposal to landfills.

Many developed countries now have effective means for statistical collection of the quantity of waste being disposed of to landfills, and are also improving their understanding of the composition of various waste categories.

Historical knowledge of waste disposal is often less accurate: waste statistics for the UK, for example, are of very limited quality before 1974 - prior to that date, responsibility for waste disposal was at a local level, and was not nationally co-ordinated (Department of the Environment, 1993).

Similarly, many countries have poor records on numbers of landfills, especially of older closed sites. US EPA (1993*b*) estimates that in the US, approximately 3,000 small landfills closed during the 1980s, additionally that there may be tens of thousands of landfills that closed prior to this. In many countries, the existence of older closed sites may be known but no records of waste types or quantities are available.

For most countries, limitations on funds available will prevent extensive investigations of these older closed sites, except for those that are still causing local environmental concern. It is therefore more cost-effective to concentrate efforts into improving the quality of data being collected on existing landfilling operations, including on the total waste to landfill quantity plus more detailed site-specific landfill data. Detailed site investigations, for example in connection with a gas exploitation scheme, may give additional support to emissions predictions, or can be used to support predictive methodologies as with the US EPA's (1993b) method.

Composition of waste is very important in determining the amount of methane generated. The *degradable organic carbon* (DOC) of waste is an essential component in all calculations of methane emissions, and small variations in the assumed values for DOC can result in large variations in the overall estimate of methane emissions. As further information becomes available about the composition of a country's waste, so it can be categorised into fractions with varying decomposition half lives, for incorporation into kinetic models.

Different countries have widely differing MSW compositions: developing countries have solid waste with a higher putrescible fraction compared with developed countries, where waste has a much higher paper and card content. These factors influence both the rate and the extent of degradation of the various waste fractions, and need to be taken into account where data are available.

For example, the amount of municipal waste landfilled in the United States is estimated at approximately 334 Mt (US EPA, Office of Solid Waste [OSW], 1988). This figure represents one of the largest uncertainties in the current US estimates. Paper was the largest single component of the degradable organic carbon (DOC) fraction in both the United States and Canada. Per capita MSW generation was in the range of 1.7 to 1.8 kg/person/day for both the United States and Canada (US EPA, 1990; El Rayes and Edwards, 1991). The average MSW generation rate in other OECD countries is 0.8 kg/person/day. MSW in these countries has a DOC content of approximately 15.3 per cent (Davis et al., 1992). The value used for the United States is for MSW only; an additional 15 Mt/yr of biodegradable industrial solid waste is also landfilled (US EPA, 1987). This industrial solid waste is unaccounted for in the initial estimates of landfill methane.

In most cases, country-specific information does not state specifically whether industrial waste is disposed of together with MSW.

Information on the amount of MSW generated and landfilled in the European countries that are not OECD members and the former Soviet Union is limited. Average MSW generation for Greece, the former Soviet Union, and Eastern Europe is approximately 0.6 kg/person/day (Frantzis, 1988; Papachristou, 1988; Peterson and Perlmutter, 1989 and Bingemer and Crutzen, 1987), and the available data indicate that putrescibles make up a large portion of the MSW (estimates range from 32 to 60 per cent). This MSW contains approximately 15 per cent DOC (Frantzis, 1988; Papachristou, 1988; Peterson and Perlmutter, 1989; Bingemer and Crutzen, 1987; Zsuzsa, 1990).

For most Asian countries, estimates of MSW generation were identified for one or two major cities, but not for the entire country. National per capita MSW generation estimates were identified for Indonesia, Sri Lanka, the Philippines, Singapore, Taiwan, and Pakistan. These estimates range from 0.4 kg/person/day for the Philippines to 1.0 kg/person/day for Singapore. The average per capita MSW generation for these countries is estimated to be 0.6 kg/person/day (Davis et al., 1992).

Few data are available on MSW production and management in Central America, South America, the Caribbean Islands, and Mexico. Most of the available information is only for the larger cities. The average per capita MSW generation rate in Costa Rica, and Mexico and six South American countries (Brazil, Colombia, Chile, Paraguay, Peru, and Venezuela) is estimated to be 0.8 kg/person/day. The components are mainly vegetable and putrescible waste paper and cardboard. The average DOC for the mentioned countries is 17 per cent (Davis et al., 1992).

Information on MSW generation and disposal for African and Middle Eastern countries is very limited. In Africa, it appears that toxic and hazardous industrial and commercial wastes are purposely or inadvertently disposed of with the MSW stream. Some information pertaining to generation rates for African countries was located; but information for only two Middle Eastern countries, Israel and Yemen, was obtained. Based on the very limited information for these two continents, it is estimated that per capita generation rates range from 0.3 to 1.1 kg/person/day, and the DOC content ranges from 3 to 20 per cent. (Thorneloe, 1993*a*)

Landfill and waste management practices also have significant effects on methane generation, for example the degree and type of landfill cover, the method of landfilling, the water management practices etc. Future changes in waste management practices will change the composition of waste to landfill considerably, resulting in different methane emissions levels.

Flaring and gas recovery schemes

Flaring and gas recovery schemes will reduce the amount of uncontrolled methane emissions from landfills. Utilisation and/or flaring of landfill gas as an energy source is one of the most successful methods for reducing uncontrolled methane emissions from landfills.

Gas flaring generally occurs where it is necessary to ensure local site safety, but it is now recognised as a valuable method for reducing the extent of methane emissions to atmosphere.

Any national inventory of methane emissions from landfills therefore needs to take into account the reductions achieved by these two factors. For gas use, the number of schemes are generally well known and documented, therefore an accurate estimate can be made of the amount of methane being used in the schemes. Information on landfill gas schemes around the world is available from a variety of sources, e.g. Governmental Advisory Associates (1991) for the US; Landfill Gas TRENDS (1993) for the UK; Gendebien et al. (1992) for the European Community; Lawson (1991) for countries participating in the International Energy Agency's Bioenergy Agreement; Richards (1989) for world statistics, etc. Most of these sources update their information regularly as more schemes are commissioned.

Estimates of the extent of flaring are more difficult to achieve with accuracy, and generally have to be estimated from a knowledge of the state of landfill management within the country. For many countries, new legislation will ensure that most future landfills will be obliged to have gas control equipment installed; therefore in the future this will result in reductions in uncontrolled emissions as well as better quality data on this factor.

6.2.6 Availability and quality of data

Waste management data

The quality of methane emissions estimates are directly related to the quality of the waste management data used to derive these estimates, i.e. data on MSW generation rates, and on quantities of MSW disposed of to landfill. Most developed countries have these data available, and they should be used wherever possible. These data are often lacking however for developing countries and for the former Communist bloc countries.

Some global compilations of data have been made that can be used where local data are not available:

- Thorneloe et al. (1993) has compiled data on waste management activities;
- Thorneloe et al. (1994) compiled data on waste management activities;
- World Resources Institute (1990) summarised waste generation rates for some countries, including Eastern European countries;
- Piccot et al. (1990) collected waste generation data;
- Bingemer and Crutzen (1987) compiled regional data;
- Carra and Cossu (1990) compiled data from 15 countries;
- OECD (1989) compiled country-specific data;
- US EPA (1993c) compiled data on global waste management activities;
- US EPA (1994*a*) Report to Congress on Global Anthropogenic Emissions of Methane have compiled a list of over 50 references on global waste generation data.

Historical data on the amount of MSW disposed of to landfill are usually of limited value or quality. Extrapolation to future waste management scenarios is usually easier, especially since many countries are modifying their waste management policies, in particular to promote waste reduction and recycling, and so are required to review and monitor total MSW generation rates and disposal routes to provide current and future waste disposal scenarios (e.g. Van Amstel et al. (1993) for the Netherlands, US EPA (1993b) for the US).

Waste composition data

The composition of waste directly determines its DOC value. Default factors provided by Bingemer and Crutzen (1987) should be used where no country-specific factors are known.

As with waste management data, above, many countries are improving the quality of data held on waste composition, because of changes to waste management policies that are encouraging reduction and recycling.

Gas flaring and use

Accurate statistics are available in most of the countries where landfill gas use is practised. However, the extent of gas flaring is often less well documented. Improvements to waste management practices should see an improvement in the collection of regular statistics which monitor the numbers of sites where gas is flared or used.

6.2.7 Conclusion

A methodology is presented here that allows simple calculation of methane emissions from landfills globally, and can be used by all countries. Some of the assumptions used in the method are open to criticism however, therefore countries are encouraged to progress to using a more sophisticated method with more country-specific data when more data become available.

6.3 Methane Emissions From Wastewater Treatment

6.3.1 Introduction

Methane (CH_4) production from wastewater treatment (WWT) under anaerobic conditions is estimated to range from 30 to 40 teragrams per year (Tg/yr). This represents 8 to 11 percent of the total global anthropogenic methane emissions, estimated at 360 Tg/yr (IPCC, 1992). Industrial WWT sources are estimated to be the major contributor to WWT emissions, accounting for 26 to 40 Tg/yr. Domestic and commercial WWT is estimated to emit approximately 2 Tg/yr, with Asia accounting for 65 percent of that amount. Uncertainty in these estimates result from a lack of data characterising wastewater management practices, the quantities of wastewater that are anaerobically treated, data on the extent that CH_4 produced is flared or otherwise utilised, and field data on the CH_4 emission potential of wastewater treatment lagoons (Thorneloe, 1993*b*).

Wastewater can produce methane if it is treated anaerobically . Anaerobic methods are used to treat wastewater from municipal sewage and from food processing and other industrial facilities, particularly in developing countries. In contrast, developed countries typically use aerobic processes for municipal wastewater treatment or anaerobic processes in enclosed systems where methane is recovered and utilised.

This section provides an explanation of the default methodology for estimating CH_4 emissions from WWT. A discussion of the uncertainty involved with these calculations is included.

6.3.2 Background

Highly organic waste streams including municipal wastewater and wastewater from industries such as food processing and pulp and paper plants have a high potential for CH_4 emissions. These waste streams quickly deplete available oxygen as their organic matter decomposes. The organic content or "loading" of wastewater is expressed in terms of biochemical oxygen demand (BOD), which is the principal factor determining methane generation potential of wastewater. BOD represents the amount of oxygen consumed by the organic material in the wastewater during decomposition (expressed in milligrams per litre - mg/l). A standardised measurement of BOD is the "5-day test" denoted as BOD_5. The maximum, or ultimate BOD is denoted as BOD_u. Untreated municipal waste streams typically have a BOD_5 ranging from 110 to 400 mg/l. Food processing facilities, such as fruit, sugar and meat processing plants, creameries, and breweries can produce untreated wastewater with a BOD_5 as high as 10,000 to 100,000 mg/l (Thorneloe, 1993*b*). Most other industrial wastewater has a low BOD content.

Under the same conditions, wastewater with higher BOD concentrations will yield more CH_4 than wastewater with relatively lower BOD concentrations. Because of its influence on CH_4, BOD is a commonly measured parameter and data is available on BOD loading rates. Table 6-2 shows BOD values for municipal wastewater by region, while Table 6-5 includes BOD values for the wastewater of key industries.

TABLE 6-2
ESTIMATED BOD$_5$ VALUES IN MUNICIPAL WASTEWATER BY REGION

Region	BOD$_5$ Value (kg/capita/day)	BOD$_5$ Value Gg/1000 persons/yr
Africa:	0.037	0.0135
Asia, Middle East, Latin America:	0.04	0.0146
N. America, Europe, Former USSR, Oceania:	0.05	0.0182

Source: US EPA (1994)

Five-day BOD can range from 0.023 - 0.091 kg/capita/day for municipal wastewater. Per capita municipal wastewater BOD$_5$ has been reported from 0.023 - 0.045 kg/day in developing countries and from 0.024 - 0.059 kg/day in developed countries (the lower value was reported for rural France) (Mara, 1976). The BOD increases when substantial amounts of kitchen wastes are discharged to sewers, for instance as the result of using sink disposals (Thorneloe, 1993*b*).

Treatment of wastewater and its residual solids by-product (sludge) under anaerobic conditions results in CH$_4$ emissions. Wastewater treatment in developed countries typically occurs aerobically using aerated impoundments. Digesters are also often used and the gas is either flared or utilised. Wastewater in these countries is not expected to be a major source of CH$_4$. However, facultative and anaerobic lagoons are often used for storage and treatment. EPA estimated in 1987 that there are approximately 5,500 municipal waste stabilisation lagoons in the United States which treat 5.2 x 10^6 m^3/day of wastewater from 8 percent of the population served by municipal treatment systems (Office of Municipal Pollution Control, 1987). The CH$_4$ potential from these lagoons is not well understood and little field data are available. Industrial and commercial wastewater processes also use lagoons for treatment and storage.

Methane production varies depending upon temperature, retention time, BOD loading, and lagoon maintenance. Facultative lagoons, the most common type, treat wastewater by both anaerobic fermentation and aerobic processes. At the bottom of the lagoon, where an anaerobic environment exists, organic matter is digested to CH$_4$ and CO$_2$. As these gases bubble to the surface, much of the CO$_2$ is adsorbed by algae and is used, along with nutrients liberated during digestion, to produce algal biomass (University of California, 1984). Aerobic conditions, supported by algae growth, are maintained near the surface. Between 20 and 30 percent of the BOD loading to a facultative pond is anaerobically metabolised. As BOD loading increases and natural surface aeration diminishes, facultative lagoons proceed to a more anaerobic state. This results in higher CH$_4$ production, providing that the temperature is higher than 15°C. Under these conditions, a facultative lagoon may act more as an anaerobic pond, with possibly 95 percent of the lagoon volume functioning anaerobically. Fermentation, and thus CH$_4$ production, is negligible at temperatures below about 15°C, at which point the lagoon serves principally as a sedimentation tank (Gloyna, 1971).

The depth of the lagoon is also an important factor in CH$_4$ production. Shallow lagoons, one metre or less in depth, are not expected to produce large quantities of CH$_4$ because the intake of oxygen from the surface, as well as the production of oxygen due to photosynthesis, prevent the formation of a significant anaerobic zone. Facultative lagoons are typically 1.2 to 2.5 metres in depth; lagoons greater than 2.5 metres in depth are typically referred to as anaerobic lagoons. The last important factor influencing the production of CH$_4$ is the retention time (Thorneloe, 1993*b*).

6.3.3 Methodology for Estimating Emissions from Wastewater Treatment

Methane emissions from wastewater treatment should be calculated for two different wastewater types:

1 Domestic and Commercial wastewater

2 Industrial wastewater

For each category, a simple methodology for calculating methane emissions from wastewater treatment is based on BOD loading and relies on available country-specific data. A standard methane conversion factor of 0.22 Gg CH_4/Gg BOD is recommended for both wastewater types. In each category a more detailed approach is also discussed. The more detailed approaches would produce more accurate results if input data are available. These data are not readily available now for many countries, but they may be in the future as research continues.

In estimating N_2O and CH_4 from wastewater, it is possible to base the calculation on total volatile solids instead of BOD if this type of data is more readily available. Such an estimate had been carries out by Loreto Donoso of the Atmospheric Chemistry Laboratory of the Instituto Nacional de Investigaciones Cientificas (IVIC) in Caracas, based on Manzanero (1986) and Abreu and Velazquez (1990). See Metcalf and Eddy, Inc. (1979), and Debruyn (1994a & b).

TABLE 6-3
ANAEROBIC AND AEROBIC METHODS OF WASTEWATER TREATMENT

Treatment Method
Aerobic treatment methods (low CH_4 potential): Developing countries • Open Pits/Latrines • Aerobic (shallow) ponds • Ocean Dumping • River Dumping Developed countries • Sewer systems with aerobic treatment
Anaerobic treatment methods (high CH_4 potential): Developing countries • Anaerobic (deep) ponds • Sewer systems with anaerobic treatment. Developed and developing countries • Septic Tanks
Anaerobic Methods with Methane Recovery Primarily developed countries

TABLE 6-4
ESTIMATED TOTAL (URBAN) WASTEWATER FRACTION ANAEROBICALLY TREATED

Region	Fraction Treated
Africa, Latin America, Asia	less than 0.10
Oceania, North America, Europe	0.15

Source: US EPA (1994). Values for Africa, Asia and Latin America have been modified downward here based on comments from the Expert Group.

Note: For many developing countries, industrial wastewater is often discharged with domestic wastewater.

Estimate methane emissions from domestic and commercial wastewater treatment

Steps for Method A (simplified approach)[1]

Data needed are:

1 Biochemical oxygen demand in Gg BOD_5 per 1000 persons per year (default values are shown in Table 6-2 for different regions.)

2 Country population in thousands (developing countries may choose to estimate wastewater treatment emissions based only on the urban population of the country if wastes produced in rural areas decompose in an aerobic environment – see Table 6-3 for list of anaerobic and aerobic treatment methods).

3 Estimate fraction of total wastewater that is treated anaerobically. Wastewater treatment methods that may result in anaerobic decomposition of waste are listed in Table 6-3. Because published data on the fraction of wastewater that is anaerobically treated in different countries are scarce, countries are encouraged to provide their own estimate based on their available data. Table 6-4, however, contains default values for the fraction of total wastewater that is treated anaerobically in certain regions – these values may be used in the absence of country-specific estimates.

4 Estimate CH_4 emission factor. The recommended default value is 0.22 Gg CH_4/Gg BOD_5.

5 Subtract the amount of methane, if any, that is recovered and thus not emitted to the atmosphere. This would include any methane recovered and either flared or used for energy as part of wastewater treatment. If no national data are readily available, the default assumption is that this amount is zero.

Equation 3 summarises the methane emissions calculation.

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[1] This method is based on the approach developed for the Wastewater Treatment Chapter of EPA (forthcoming) and is described in Thorneloe (1993b).

EQUATION 3

$$\text{Methane emission (Gg/yr)} = \text{Population } (10^3) \times \text{Gg } BOD_5/1000 \text{ persons/year} \times \text{Fraction Treated Anaerobically} \times 0.22 \text{ Gg } CH_4/\text{Gg } BOD_5 - \text{Methane Recovered (Gg)}$$

Steps for Method B (detailed approach)

A more precise estimate of methane emissions from wastewater treatment for a given country is possible if the following additional data are available: 1) The different treatment methods that are used in each country and the total portion of wastewater that is treated using each of these methods; and, 2) the methane conversion factor (MCF) for each of these treatment methods (the MCF represents the extent to which the maximum methane producing capacity of the wastewater is realised for a given wastewater treatment system).

Unfortunately, many countries are not likely to have data on the portion of wastewater treated using different methods. This is likely to be the case for many developing countries, which are of particular importance because of their reliance on anaerobic treatment methods. Additionally, at this time, complete information on MCFs for different wastewater treatment systems is not available. Countries which have more detailed information on specific treatment methods and their MCFs are encouraged to use this information in preparing national emissions estimates and to report these results to the IPCC. Through review of such estimates and results of ongoing research, a more comprehensive data base of MCFs for specific treatment methods may be developed in the future.

Where these data are available, the following approach would be used to estimate methane emissions from wastewater treatment:

Data needed are:

1 Country population (thousands).

2 Biochemical Oxygen Demand (Gg BOD_5 per 1000 persons per year).

3 Fraction of total wastewater treated using different treatment methods. Some common methods are listed in Table 6-3.

4 The CH_4 emission factor. The recommended default value is 0.22 Gg CH_4/Gg BOD_5.

5 The MCF (methane conversion factor) of each wastewater treatment method.

Equation 4 summarises the calculation of methane emissions from each wastewater treatment system (j) using the more detailed approach. Total emissions are the sum of emissions from all systems.

EQUATION 4

$$\text{Methane emission (Gg/yr)} = \sum_{i} \text{Population } (10^3) \times \text{Gg BOD}_5/1000 \text{ persons/year} \times \text{Fraction Wastewater Treated using Method}_i \times 0.22 \text{ Gg CH}_4/\text{Gg BOD}_5 \times \text{Methane Conversion Factor (MCF) for Method}_i - \text{Methane Recovered}$$

Estimate methane emissions from industrial wastewater treatment

Methane emissions from wastewater produced in a few key industries are estimated to account for a very large portion of total methane emissions from wastewater treatment (Thorneloe 1993*b*). Table 6-5 lists industries which are believed to be responsible for most of the emissions. National experts should estimate emissions for these industries, if applicable, and any others which can be estimated to have significant emissions, based on locally available data.

Steps for Method A (Simplified Approach)

1 Determine the relevant industries for a given country. The methane emissions from industrial wastewater treatment are based on wastewater outflow by industry. Table 6-5 lists industries which produce wastewater containing high concentrations of organic material likely to produce significant CH_4 emissions.

2 Wastewater outflow by industry must be estimated. If these data are not directly available, they may be estimated based on production by industry, and water consumed per unit of product. Typical water consumption rates for some key industries are presented in Table 6-6.

3 The BOD_5 concentration of the wastewater for each type of industry must be estimated. Default BOD values are provided in Table 6-5.

4 Estimate the fraction of wastewater from each industry that is treated anaerobically. Unfortunately, default values are not available by industry. If no information is locally available, the default values shown in Table 6-4 could be used as an initial approximation.

5 Estimate CH_4 emission factor. The recommended default value is 0.22 Gg CH_4/Gg BOD_5.

6 If anaerobic treatment with methane recovery is employed, the amount of methane that is recovered should be subtracted from total emissions.

TABLE 6-5
BIOCHEMICAL OXYGEN DEMAND (BOD) CONCENTRATION ESTIMATES FOR VARIOUS INDUSTRIAL WASTEWATERS

Industry[a]	BOD (kg/l)	References and Notes
Iron and Steel	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Non-ferrous metals	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Fertiliser	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Food & Beverages	0.035	This value is an average of the following categories of the food & beverage industry.
Fruits/vegetables	0.003	Barnes et al. (1984), p. 213
Cereals	0.001[c]	EPA (1974*a*), pp. 39, 40
Meat Packing	0.020[c]	EPA (1975), pp. 58, 60; EPA (1974*c*), pp. 39, 41
Butter	0.003[c]	EPA (1974*b*), p. 59; Barnes et al. (1984), p. 316
Cheese	0.003[c]	EPA (1974*b*), p. 59; Barnes et al. (1984), p. 316
Cane Sugar	0.002[b]	Barnes et al. (1984), p. 20
Beet Sugar	0.010[b]	Barnes et al. (1984), p. 12; EPA (1974*d*)
Wine	0.135[c]	Barnes et al. (1984), p. 73
Beer	0.085[c]	Barnes et al. (1984), p. 73
Other Beverages	0.083[c]	Barnes et al. (1984), p. 73
Pulp and Paper	0.004[b]	Carmichael and Strzepek (1987), p. 49 and Hall et al. (1988) as cited in Torpy (1988), p. 20
Petroleum Refining (Petrochemical)	0.004[c]	Average of values reported in Carmichael and Strzepek (1987), pp. 33, 36
Textiles	0.001[b]	Carmichael and Strzepek (1987), p. 67
Rubber	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Miscellaneous[d]	0.002	No BOD values obtained. Used BOD reported for the pharmaceutical Industry in Carmichael and Strzepek (1987), p. 85

[a] Industries presented here are taken from table 47, pp. 116, 117 in Carmichael and Strzepek (1987).

[b] Reported as BOD. This is assumed to be ultimate BOD.

[c] Reported as BOD_5.

[d] Industries in this group were undefined.

Source: Thorneloe, 1993*b*.

TABLE 6-6
WATER CONSUMPTION PER UNIT OF PRODUCT AT KEY INDUSTRIAL FACILITIES

Process	Water Consumption[a] (litres/ tonne)
Canneries	
- Green beans	80,000
- Peaches and pears	22,000
- Other fruits and vegetables	8,000-40,000
Food and Beverage Industry	
- Beer	60,000
- Wine	20,000
- Meat packing	16,00-20,000 (live weight)
- Dairy products	
- Sugar	
Pulp and Paper	
- Pulp	344,000-966,000
- Paper	200,000
Textiles	
- Bleaching	300,000-400,000 (cotton)
- Dyeing	40,000-80,000 (cotton)

Sources:

a Metcalf and Eddy (1972).

b US EPA (forthcoming).

* These were reported as BOD and are assumed to be ultimate BOD, as opposed to BOD_5. These values, however, should still be used as the default assumptions, as other data are not available

These water consumption factors are approximate, and in some cases, the water used in the process may not all become wastewater.

Equation 5 summarises the emissions calculation for industrial wastewater treatment. Emissions should be estimated for each industry; total emissions from industrial wastewater treatment are the sum of emissions from each industry.

EQUATION 5

$$\text{Methane emission (Gg/yr)} = \sum \text{Wastewater outflow by industry (Ml/yr)} \times \text{kg } BOD_5\text{/l} \times \text{Fraction Wastewater Treated Anaerobically} \times 0.22 - CH_4 \text{ Recovered (Gg/yr)}$$

Method B (detailed approach)

As with estimating methane emissions from domestic and commercial wastewater treatment, more precise estimates of methane emissions from industrial wastewater treatment can be made if specific methods used to treat wastewater from each industry are known and the MCFs for each method have been estimated.

If this information is available, Equation 6 can be used to calculate emissions from industrial wastewater treatment. Total emissions for each industry are the sum of emissions from each wastewater treatment system. Total emissions from industrial wastewater treatment are the sum of emissions from each industry.

EQUATION 6

$$\text{Methane emission (Gg/yr)} = \sum \text{Wastewater outflow by industry (Ml/yr)} \times \text{kg BOD}_5\text{/l} \times \text{Fraction Wastewater Treated by Method}_i \times 0.22 \times \text{Methane Conversion Factor (MCF) of Treatment Method}_i - \text{CH}_4 \text{ recovered (Gg/yr)}$$

6.3.4 Global Emissions Estimates

Thorneloe (1993*b*) provides country-specific CH_4 emission estimates obtained by using the simple methods described above and readily available country and region-specific data and assumptions. Results by country are summarised in Table 6-7 for domestic waste and by industry for industrial waste in Table 6-8. Both calculations assume approximately 10-15 percent of wastewater is anaerobically. See Thorneloe (1993*b*) for a discussion of regional and country-specific information used to develop these estimates.

TABLE 6-7
ESTIMATE OF GLOBAL AND COUNTRY-SPECIFIC METHANE EMISSIONS FROM THE TREATMENT OF DOMESTIC WASTEWATER - 1990 (TG/YR)

Country	*Emissions*
Africa[a]	
Egypt	0.02
Kenya	0.01
Morocco	0.01
Nigeria	0.04
South Africa	0.01
Sudan	0.01
Tanzania	0.01
Uganda	0.01
Other Africa	0.09
Total Africa	**0.21**
Asia[b]	
China	0.54
Korea, N.	0.01
Vietnam	0.03
Other Asia	0.92
Total Asia	1.50
South America[a]	
Argentina	0.01
Brazil	0.05
Colombia	0.01
Mexico	0.03
Venezuela	0.01
Other So. America	0.02
Total South America	**0.13**
North America[b]	
Canada	0.02
United States	0.15
Other No. America	0.04
Total North America	**0.21**
Europe	
France	0.01
German Democratic Republic	0.01
Italy	0.01
United Kingdom	0.01
Total Europe	**0.04**
Former USSR[b]	**0.18**
Oceania[b]	
Australia	0.01
Total Oceania	**0.01**
World Total	**2.30**

a. Ten percent of wastewater is assumed to be anaerobically degraded.

b. Fifteen percent of wastewater is assumed to be anaerobically degraded.

TABLE 6-8
ESTIMATE OF GLOBAL METHANE EMISSIONS FROM INDUSTRIAL WASTE WATER TREATMENT 1990
(TG/YR)

	Developed Countries				Developing Countries				World-wide			
Industry	Industrial Waste-water Outflow[b] (Millions m^3/yr)	BOD5 (kg/l)	Percentage of Waste-water Anaerobically Degraded		Industrial Waste-water Outflow[b] (Millions m^3/yr)	BOD5[c] (kg/l)	Percentage of Waste-water Anaerobically Degraded		Industrial Waste-water Outflow[b] (Millions m^3/yr)	BOD5[c] (kg/l)	Percentage of Waste-water Anaerobically Degraded	
			10%	15%			10%	15%			10%	15%
			Emissions				Emissions				Emissions	
Iron & Steel	168,000	0.001	4	6	56,000	0.001	1	2	224,300	0.001	5	7
Non-Ferrous Metals	26,600	0.001	1	1	8,850	0.001	0	0	35,000	0.001	1	1
Fertiliser	14,300	0.001	0	1	4,500	0.001	0	0	19,000	0.001	0	1
Food & Beverages	7,700	0.035	6	9	2,600	0.035	2	3	10,300	0.035	8	12
Pulp & Paper	33,300	0.004	3	4	11,100	0.004	1	2	44,400	0.004	4	6
Petroleum Refining	54,700	0.004	5	7	18,200	0.004	2	2	73,200	0.004	6	10
Textile	34,600	0.001	1	1	11,450	0.001	0	1	46,100	0.001	1	2
Rubber	6,800	0.001	0	0	2,300	0.001	0	0	9,100	0.001	0	0
Miscellaneous[a]	9,500	0.002	0	1	3,200	0.002	0	0	12,700	0.002	1	1
TOTAL	355,500		20	30	118,200		6	10	474,100		26	40

a. This group was undefined in Carmichael & Strzepek (1987).

b. Carmichael & Strzepek (1987).

c. Sources of BOD values are given in Table 6-5.

6.3.5 Uncertainties

When trying to create wastewater CH_4 emissions estimates, there are several factors which contribute to the uncertainty of these figures.

Wastewater Quantities

Often the specific volumes of municipal and industrial wastewater outflow and the volumes treated under anaerobic conditions in each country are not well known. As a result, data limitations exist for quantifying the fraction of wastewater subject to anaerobic decomposition. The effect of recycling industrial wastewater outflow is also not well understood.

Data are needed for specific volumes of wastewater being processed through anaerobic decomposition. Currently, a large volume of the world's wastewater is emitted to lakes, rivers, and oceans without any kind of treatment, or is deposited in various systems such as pit toilets or merely on the ground and not contained in any way. These are briefly discussed below.

Additional Wastewater Treatment Methods

No information is readily available on CH_4 emitted from unsewered wastewater treated in septic systems, pit toilets or cesspools. Emissions from these systems might be considerable if factors such as temperature, retention time, and system configuration are favourable. The CH_4 could be emitted through vent pipes in the systems or through cracks and leaks in the tanks, assuming that CH_4 is not completely oxidised in surrounding soil.

Discharge into surface waters

In many places, municipal wastewater is discharged into surface water without treatment. In cases in which the receiving surface water has adequate oxygen, very little or no anaerobic activity is expected. For example, discharge well offshore into the ocean would probably not result in anaerobic activity. Similarly, discharge into lakes and rivers that have adequate oxygen to support aquatic life (particularly fish) would not be expected to result in methane emissions. Alternatively, when municipal wastewater is discharged into marshy areas or lakes and rivers that are oxygen deficient, methane is probably going to be produced. The extent of methane production has not been well quantified. It is not expected that all the organic matter in the wastewater would decompose anaerobically because there is generally at least some amount of oxygen available for aerobic decomposition. The following initial guidance is offered.

- Discharge into surface waters (not anaerobic): less than 1 per cent of the organic material decomposes anaerobically – default factor of 0 per cent.
- Discharge into anaerobic surface waters (marsh, river or lake that cannot support aquatic life, e.g., fish): 25 to 75 per cent of the organic material decomposes anaerobically – default factor of 50 per cent.

Septic Tanks

Septic tanks are commonly used for individual residences or small collections of buildings or facilities when centralised wastewater collection and treatment is not feasible or available. Septic tanks generally are designed to retain and anaerobically treat solids while allowing liquids to pass through the system to a drainage field within 24 hours. Solids are periodically removed, (i.e. pumped out) since they collect in the septic tank. A properly designed and operating septic tank may require pumping out once a year or less frequently. Frequent solids removal (e.g., monthly) reduces the extent of anaerobic decomposition that takes place by reducing the residence time of the organic material. The drainage field that receives the liquid is generally expected to be aerobic, and would not expect to contribute to methane emissions. While measurements are required to provide a basis for estimating emissions from this source, the following general guidance is offered:

- Septic tanks with long solids retention times (i.e., pumped out no more frequently than once every six months): 25 to 75 per cent of the organic matter decomposes anaerobically – default factor of 50 per cent.

- Septic tanks with short solids retention times (i.e., pumped out more frequently than once every six months): 0 to 30 per cent of the organic material decomposes anaerobically – default factor of 10 per cent.

Open Pits and Latrines

Open pits and latrines are used in may areas to manage human waste. Generally of very primitive designs, these facilities are often simply holes dug in the ground. The extent of anaerobic decomposition achieved will depend strongly on local conditions and operating practices. While measurements are required to provide a basis for estimating emissions from this source, the following general guidance is offered:

- Based on the information available regarding the anaerobic decomposition of livestock manure managed in pits, about 5 to 65 per cent of the organic material decomposes anaerobically – default factor of 20 per cent.

In many warmer regions of the world sewage may be discharged into dry riverbeds, and into rivers that are intermittently dry or have periods of extended low flow such that there is no water to serve as a receiving body for the wastewater (UNEP, 1980; WHO, 1987). Anaerobic conditions can develop in these instances (UNEP, 1988, 1980). No data are available on this topic.

Sewage sludge spread on land can result in a carbon sink. The development of a methodology for calculating this sink has been identified as an area for future work. The practice of spreading sewage sludge on land can also increase soil carbon. Thus, an analysis of the issue of sewage sludge spread on land should also consider the impact of this practice on GHG emissions from agricultural soils.

Wastewater Treatment Facility Efficiency and Output

Wastewater supposedly treated aerobically by treatment plants may still be subject to anaerobic conditions, due to poorly functioning facilities. In addition, adjustments should be made for (1) the amount of CH_4 that is controlled through utilisation or flaring and (2) the amount of CH_4 that is oxidised prior to atmospheric release. However, the specific data needed are often not available.

Research in Japan has produced data on high levels of methane production resulting from a wastewater treatment process that includes aeration and is essentially operated under aerobic conditions. (Kyosai and Mizuochi, 1993) This represents an area that should be studied in more detail in the future.

Current estimates from wastewater treatment lagoons are relatively uncertain due to the limited available data. The US EPA's Office of Research and Development's Global Climate Change Engineering Research Program is conducting field measurements of wastewater treatment lagoons, both anaerobic and facultative, to develop emission factors from these sources.

Physical and Chemical Data

Data on physicochemical wastewater characteristics are limited, especially for country-specific wastewater volumes. For industrial wastewater emission estimates, the BOD values reported for the source categories are averages of BOD values given for wastewater streams from several processes. The estimate could be improved if data were obtained on the chemical characteristics and volumes of process wastewater streams and the fraction of these wastewater streams anaerobically degraded. Furthermore, the emission methodology does not account for factors, such as temperature, pH and retention time, that influence the rate and extent of anaerobic decomposition, and consequently, the potential for CH_4 production.

6.3.6 Conclusion

The methodology presented in this section gives a simple calculation of methane emissions from wastewater and can be used by all countries. Some of the assumptions used in the method are open to criticism. Therefore countries are encouraged to progress to using a more sophisticated method with more country-specific data, when more data become available.

6.4 Emissions From Waste Incineration

6.4.1 Introduction

Waste incineration like other types of combustion, is a source of GHG emissions. Few data have been compiled on the global emissions from waste incineration. Preliminary indicators are that this source represents a small percentage of the total GHG output from the waste source category.

6.4.2 Emissions

Certainly waste incineration produces CO_2, but it is difficult to identify the portion which should be considered **net** emissions. A large fraction of the carbon in waste combusted (e.g. paper, food waste) is derived from biomass raw materials which are replaced by regrowth on an annual basis. These emissions should not be considered net anthropogenic CO_2 emission in the IPCC methodology. If the agricultural or forestry sources are not being sustainably managed, net CO_2 emissions (equivalent to reductions in biomass stocks) should be accounted for in those source categories. On the other hand, some carbon in waste is in the form of plastics or other products based on fossil fuel. Combustion of these materials, like fossil fuel combustion, releases net CO_2 emissions. In estimating emissions from waste incineration, the desired approach is to separate carbon in the incinerated waste into biomass and fossil fuel based fractions. Only the fossil based portion should be considered net carbon emissions. Any such detailed analysis should ensure that carbon emission are not double counted in the treatment of stored carbon under energy emissions. See *Overview to the IPCC Guidelines.* A recent Belgian analysis (Debruyn and Van Rensbergen, 1994) offers an example of a very detailed approach.

Other relevant gases released from combustion are net GHG emissions. Methane emissions from waste incineration are highly uncertain. An expert working group recognised waste incineration as a source of methane production, but was not able to give global estimates or default emissions factors. Although this source is considered to be relatively small compared to the other CH_4 sources in waste, it was recognised as an area for further research in the future (Berdowski et al., 1993).

Recent studies have also shown that N_2O may be an important GHG produced from incineration. Table 6-9 provides data from studies of several incineration plants and the N_2O produced from the waste incineration (de Soete, 1993). Studies in Belgium (IPCC, 1993), Japan (Tanaka et al., 1992) and Norway (Rosland, 1993) have estimated N_2O production from their waste incineration processes. It has also been found that the emission level depends on the nature of the waste burned. Research in Japan has noted that while all types of incineration produce N_2O, sludge incinerators produce the highest emissions rates (Tanaka et al., 1992).

Traditional air pollutants from combustion - NO_x, CO, NMVOC - are characterised in existing emissions inventory systems. The IPCC does not provide a new methodology for these gases, but recommends that national experts use existing published methods. Some key examples of the current literature providing methods are: Default Emission Factor Handbook (EEATF, 1992), as well as the US EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1985).

TABLE 6-9
NITROUS OXIDE EMISSIONS FROM WASTE INCINERATION

Nature of Waste (reference)	Facility	T°C	N_2O Emission				
			ppmv[1] min.	ppmv[1] average	ppmv[1] max	at O_2 (%)	g N_2O / tonne waste
Municipal refuse	10 furnaces (65-300 tonnes/day)		1.2	8	18		
Municipal refuse	Stepgrate	780-880	0.8		4.9	10	11-43
	Stepgrate	780-980	4		24	8-14	40-220
	Fluid. bed	830-850	6.7		10.5	13-15	14-123
Municipal solid waste	5 stokers (20-400 tonnes/day)		3	7	12		26-270
	3 fluid. bed		5.6	9.8	17.1		97-293
	rot. kiln (120 tonnes/day)		10.2	11.1	12.1		135-165
Sewage- sludge	4 incin. (150-300 tonnes/day)		57	87	125		
Sludge	Rotary grate	750		50.7			227
	Fluid. bed	770-812	270		600		580-1528
	"	838-854	135		292		684-1508
	"	834-844	100		320		275-886
	"	853-887	45		145		101-307

Source: de Soete, 1993.

[1] ppmv = parts per million by volume

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